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Editorial Comment

Meetings of Scientific Societies in Wartime

PLANS for a meeting of the Optical Society last February were cancelled because of the war emergency. Some members of the Society felt that this action was a mistake, since they believed that scientific meetings provide an opportunity, apart from the scheduled program, for discussions and conferences which can otherwise be arranged only with considerable difficulty. In fact, a few members argued that the holding of regular meetings actually minimizes travel, since it brings together most of the important workers in a scientific field and gives them opportunity for transacting business which might otherwise require special trips. Accordingly, Optical Society meetings were scheduled to be held during the summer at Cambridge, Massachusetts, and in October in New York City. The reasonableness of this point of view appears substantiated by the attendance at the Cambridge meeting, which exceeded 300.

A memorandum on the holding of meetings of scientific and learned societies in wartime has been prepared within the last few weeks by the Science Committee which is advisory to the National Resources Planning Board, and which is composed of members designated by the National Research Council, the American Council on Education, the American Council of Learned Societies, and the Social Science Research Council. In essence, this memorandum states that in the war period scientific societies have an important part to play in the national effort, and meetings of these societies should be so organized as to be in the best public interest. It suggests, therefore, that each society or association consider its relationship to the war effort, and plan the programs of its meetings so that the most effective contribution will be made. Insofar as possible meetings should not be held in or near defense areas, especially the ports and cities of the Atlantic seaboard, and should be scheduled for such days of the week as to avoid week-end travel. Meetings should also be distributed among different cities in order to avoid congestion at any one point, or along routes of travel.

The Committee emphasized that meetings not closely connected with the war effort should be postponed, and that attendance at all meetings should be confined to those whose presence or participation is believed to be useful. Finally, they pointed out that the above statements are based upon conditions of transportation that exist at the present time, and that changes in these conditions may take place and may necessitate radical changes in plans for meetings. The Directors of the Optical Society of America are taking these suggestions into full consideration in laying their plans for future meetings.

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The Control of Photographic Printing by Measured Characteristics of the Negative*

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A large amount of experimental data has been obtained to determine what portion of the D-log E curve of photographic paper is useful in making high quality prints. Psychophysical statistical methods were necessary in solving this problem. Special attention was given to selecting a procedure which would yield results of maximum practical significance. Prints were made from about 200 negatives using five different exposures on each of three contrast grades of paper for each negative. Most of the work was done with a normal, commercially available set of semi-matte surface papers having six different contrast grades. Additional work was done using glossy and matte surface papers. Every set of prints was judged by a number of observers to determine the best print. The location of the "first-choice" prints on their respective D-log E curves was then obtained from maximum and minimum density readings on the prints and on the negatives. The data for second-choice and third-choice prints were also obtained as a matter of general interest. It was found that the minimum or shadow density of a negative is a much more reliable guide for determining correct printing exposure than the maximum or highlight density. The integral or average density of the negative is nearly but not quite as satisfactory for this purpose as the minimum density. Of great interest is the fact that the useful maximum density of the printing paper was, on the average, considerably below the available maximum density, while the useful minimum density of the paper was usually very close to, and often equal to, zero density. The primary requirements, however, appear to be expressed by gradients rather than by densities. It was found that the limits of the useful portion of the D-log E curve of the positive material are determined very closely by fractional gradients of 0.1 $\bar{G}$ on the toe of the curve and 1.0 $\bar{G}$ on the shoulder of the curve, where $\bar{G}$ is the average gradient measured between these two limiting points. This conclusion has an important bearing on the establishment of a significant method for expressing the sensitometric characteristics of photographic papers. It leads to an evaluation of the *effective printing speed* and the *useful exposure scale* of the positive material. The proposal is made that speed be defined as $10^4/E$, where E is the exposure corresponding to the limiting gradient on the shoulder of the curve. The useful log exposure scale of the paper is defined as the log exposure interval lying between the two limiting gradients. The application of these results to the making of prints by sensitometric control is discussed. In general, a negative should be printed so that its minimum density falls on the shoulder of the D-log E curve at the point where speed is measured. A method is given whereby the density scale of the negative can be used with reasonable success to determine the proper contrast grade of paper for making the print.

I. INTRODUCTION

IN a recent communication from these Laboratories[1] the results of a study of the distribution of brightness in exterior scenes were presented. In this work the maximum, minimum, and integrated brightnesses in 126 exterior scenes were measured. The scenes were chosen to represent a wide range of compositional types. The measurements extended over a period of about 18 months and thus included seasonal variations in the brightness distribution. Furthermore, the work was done at various times during the day and under a wide variety of illuminations as determined by atmospheric conditions, such as light clouds, heavy clouds, haze, sunlight, etc.

Simultaneously with the making of the brightness measurements a photograph of each scene was made. The physical and optical characteristics of the camera-lens system used were precisely determined. The exposed materials were developed under standardized conditions along with sensitometrically exposed samples of the negative material. Maximum and minimum densities in each of the negatives were then measured and so it was possible to determine exactly what portion of the negative material characteristic curve was utilized in the making of each negative. Thus a large volume of correlated data relative to the characteristics of the scene, the camera-lens system, the negative material, and the resultant negatives was obtained. Hence there is now available a large quantity of data which can be utilized in a further study of other interesting photographic problems. For instance, many theories have been advanced as to the relation-

* Communication No. 874 from the Kodak Research Laboratories.

[1] L. A. Jones and H. R. Condit, "The brightness scale of exterior scenes and the computation of correct photographic exposure," J. Opt. Soc. Am. **31**, 651 (1941).

ship which must exist between the characteristics of a negative and those of the positive material in order that a positive of satisfactory quality shall be obtained. It seems unsafe to assume, without supporting evidence, that this relationship does not depend upon certain characteristics of the scene.

While considerable attention has already been devoted to the prediction of correct printing exposure from the measured characteristics of the negative,[2] this subject seems to merit further attention, particularly in an effort to find if possible a unique characteristic of the negative which can be measured with simple equipment by the average photographic worker and which will be a reliable guide to the computation of correct printing exposure.

It is also desirable to use measured characteristics of a negative as a guide to the choice of a contrast grade of printing paper which will yield a print of high quality. It is known in a general way that the useful exposure scale of the positive material should correspond to the density scale of the negative. However, considerable uncertainty exists regarding just what constitutes the *useful* exposure scale.

While the sensitometry of developing-out papers has been brought to a fairly high state of perfection, the practical significance of the various numbers in terms of which the characteristics of these materials are expressed is not too well understood. It is hoped that the present work will throw more light on this subject and lead perhaps to more meaningful definitions of such characteristics as speed, contrast, useful exposure scale, etc.

Since the brightness scale of an exterior scene is, in the majority of cases, greater than the available brightness scale of photographic printing papers, it is evident that considerable distortion of the tonal scale must exist in the final positive. It is of interest to discover what distortions of rendering are least detrimental to photographic quality. Direct information on this point can be obtained by determining the tone reproduction characteristics of statistically chosen high quality positives.

II. RÉSUMÉ OF THE DATA AVAILABLE FROM THE FORMER COMMUNICATION

Before proceeding with the application of these data to the problems to be discussed in the present paper, it is desirable to review briefly the former work. This can be done most satisfactorily by referring to Fig. 1. The field work consisted in the measurement of the maximum object brightness, B_0 max.; minimum object brightness, B_0 min.; and integrated object brightness, $B_0(M)$. The *brightness scale* of the object (scene) is defined as the ratio of the maximum to the minimum object brightness.

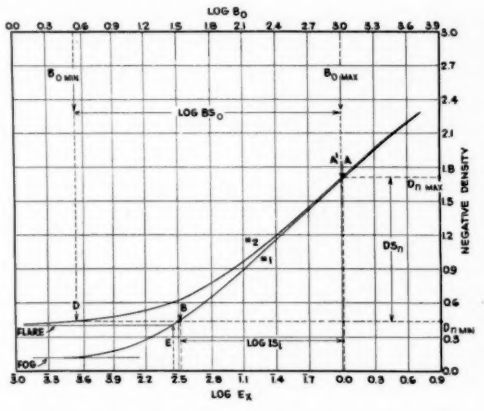

FIG. 1. Density-log exposure characteristic of the negative material.

$$BS_0 = B_0 \text{ max.}/B_0 \text{ min.}$$

From the density D, measurements made on sensitometrically exposed strips of the negative material, which were developed along with the camera-exposed negative material, the characteristic curve of the negative material, $D=f(\log E_x)$, was plotted. This is curve No. *1* in Fig. 1.

After the processing of the negatives, the average density $\bar{D}_n$,* the maximum negative density,

[2] C. M. Tuttle, "On the assignment of printing exposure by measurement of negative characteristics," J. Soc. Mot. Pict. Eng. **18**, 172 (1932); "Photoelectric photometry in the printing of amateur negatives," J. Frank. Inst. **224**, 315 (1937); "Devices for the photoelectric control of exposure in photographic printing," J. Frank. Inst. **224**, 615 (1937).

* It should be pointed out that the integrated object brightness, $B_0(M)$, is not identical with the *average* object brightness. Values of $B_0(M)$ were obtained by using an "integrating" photoelectric exposure meter. There are a number of such instruments on the market and in extensive

D_n max., and the minimum negative density, D_n min., were determined. The density scale of the negative is defined as the difference between the maximum and minimum density:

$$DS_n = D_n \text{ max.} - D_n \text{ min.}$$

The maximum and minimum negative densities were then plotted on the density scale, as shown at the right of Fig. 1. Horizontal lines through these points intersect curve *1* at the points A and B, and thus locate the portion of the characteristic curve of the negative material which was utilized in each case. Perpendiculars dropped from the points A and B to the log E_x axis give the values of maximum and minimum exposure to which the negative material must have been subjected in the camera. Since the exposure time is constant at all points on the surface of the negative material, these exposure values are directly proportional to the corresponding image illumination I_i. The *illumination scale of the image* is defined as the ratio of the maximum to the minimum image illumination:

$$IS_i = I_i \text{ max.}/I_i \text{ min.}$$

A comparison of the values of IS_i with those of BS_0 shows that the former are always less than the latter. This results from the presence of nonimage-forming light in the camera which is usually referred to as "flare light" or "flare." It arises from several sources, among which may be mentioned the interreflection between the glass-air surfaces of the lens system, reflections from the interior of the lens mount, shutter, and diaphragm blades, the interior surface of the camera, etc. The relation between the brightness scale of the object and the illumination scale of the image is a convenient and useful method for specifying the magnitude of the flare present under any particular set of conditions. The *flare factor* is therefore defined as follows:

$$FF \text{ (flare factor)} = BS_0/IS_i.$$

The magnitude of the flare factor is not determined entirely by the optical and physical characteristics of the camera-lens assembly, but depends also on the nature of the scene being photographed and its environment. The aspect of the scene and of its environment which determines flare factor is, of course, the distribution of brightness in the scene and in its environment.

The values of image illumination as determined by the method illustrated in Fig. 1* are the *total* illumination characteristics of the image. These are made up of two components, one due to image-forming light from the corresponding point in the object and the other to non-image-forming flare light. This composite character of the image illumination is designated by the following nomenclature:

$I_i = I_{io} + I_{if}$,
I_i = total image illumination,
I_{io} = image illumination due to object alone,
I_{if} = image illumination due to flare alone.

It is convenient to regard the presence of flare light in the camera as equivalent, in its effect upon the realizable object brightness scale, to the addition of a constant increment of brightness ΔB to all the actual existent brightnesses in the scene. From the data now available it is possible to compute for each of the scenes studied

use in the amateur field. The readings obtained with these instruments depend, of course, upon the particular structure, one important characteristic of which is the acceptance angle. In general, these readings are not those of the *average* brightness $\bar{B}_0$ for which the following definition appears most rational:

$$\bar{B}_0 = \frac{B_1 + B_2 + B_3 \cdots B_n}{n},$$

in which B_1, B_2, B_3, etc., are the brightness values of small elements of the scene area.

For the purposes of this discussion average negative density, $\bar{D}_n$, is defined in an analogous manner:

$$\bar{D}_n = \log 1/\bar{T}_n,$$

where

$$\bar{T}_n = \frac{T_1 + T_2 + T_3 \cdots T_n}{n},$$

in which T_1, T_2, T_3, etc., are the transmittances of small elements of the negative.

The average print density $\bar{D}_p$ is given by

$$\bar{D}_p = \log 1/\bar{R},$$

where

$$\bar{R}_p = \frac{R_1 + R_2 + R_3 \cdots R_n}{n},$$

in which R_1, R_2, R_3, etc., are the reflectance values of small elements of the positive.

* These values were determined by a method of photographic photometry and it should be remembered that there is a possibility that they may not agree perfectly with the corresponding value determined visually. However, since the negative material used in this work is panchromatic and hence sensitive to all wave-lengths of the visible spectrum, the departures which may occur are, on the average, small, especially when it is considered that the colors which are encountered in exterior scenes are associated with radiant energy compositions which usually have low physical (radiant) purity.

the value of ΔB. This is given by the following equation:

$$\Delta B = \frac{(I_i \text{ min.} \cdot B_0 \text{ max.}) - (I_i \text{ max.} \cdot B_0 \text{ min.})}{I_i \text{ max.} - I_i \text{ min.}}.$$

In practically all cases ΔB is of negligible magnitude as compared with the maximum scene brightness. This is not true, however, when it is compared with minimum scene brightness, and for some purposes it is convenient to know the *effective* minimum scene brightness, *ef* B_0 min., the value of which is given by the expression:

$$ef\ B_0 \text{ min.} = B_0 \text{ min.} + \Delta B.$$

Curve *1* in Fig. 1, which is determined sensitometrically, shows the relation between density and the exposure incident upon the negative material which, of course, in the camera is determined by the total image illumination I_i. If flare is present in the camera, this curve cannot give the relationship between negative density D_n and object brightness B_0. Since in many tone reproduction problems we are chiefly interested in the relationship between the brightness distribution in the scene and that in the final illuminated print, curve *1* does not yield the desired information. Data are now available, however, for determining the desired relationship, namely, $D_n = f(B_0)$.

Along the top of Fig. 1 is established a scale of log B_0 which may for present purposes be merely relative. The point A' is established on the horizontal line through D_n max. to the left of point A, the separation being given by

$$\log \frac{B_0 \text{ max.} + \Delta B}{B_0 \text{ max.}}.$$

The point D is located on the horizontal line through D_n min. to the left of point B, the separation being given by

$$\log \frac{B_0 \text{ min.} + \Delta B}{B_0 \text{ min.}}.$$

These points lie at the extremities of the desired relationship between negative density and log B_0. Additional points on this curve are located by taking other values of negative density and determining, in a manner similar to that used in locating A' and D, the horizontal displacement from curve *1*. Curve *2*, Fig. 1, is a result of this procedure. This curve (No. *2*) is the *characteristic* curve of a *particular negative* as distinguished from curve *1*, which is the *characteristic* curve of the *negative material*.

In the application of these data to the evaluation of tone reproduction quality and to the determination of effective camera speeds of negative materials by means of a gradient criterion, a knowledge of the gradient characteristics of curve *1*, $dD/d \log E_x$, and curve *2*, $dD/d \log B_0$, is necessary. Of immediate interest are the gradient values at the limits of the used portions of these curves. Such gradient values are referred to as limiting gradients, and, to distinguish between the gradients at the two ends of a given curve, use is made of the two words "shadow" (*s*) and "highlight" (*h*), as identifying the regions of the object tonal scale to which the limiting gradient applies. For some purposes it is also necessary to know the average gradient of the negative. This is equivalent to the slope of a straight line connecting the points D and A'. The average gradient of the used part of the negative material is given by the slope of a straight line connecting B and A.

In addition to the quantities already discussed and defined, the following values relating to various aspects of gradient can now be determined for each scene and the negative of it.

Limiting Gradients—θ

$h\theta_x$, the limiting gradient (at point A) of the used portion of the negative material in the highlight region.

$s\theta_x$, the limiting gradient (at point B) of the used portion of the negative material in the shadow region.

$h\theta_n$, the limiting gradient (at point A') of the negative in the highlight region.

$s\theta_n$, the limiting gradient (at point D) of the negative in the shadow region.

Average Gradients—ϕ

ϕ_x is the average gradient of the used portion of the negative material.

ϕ_n is the average gradient of the negative.

For all practical purposes $h\theta_x$ and $h\theta_n$ are

identical in value and no distinction need be made between these values. The limiting gradients $s\theta_x$ and $s\theta_n$ are related by the following simple expression:

$$s\theta_n = s\theta_x / FF.$$

The data taken from the previous communication[1] for use in connection with the problems of this paper may be summarized as follows:

TABLE I. Specimen data and summary. Characteristics of objects and camera images.

Scene No.	B_0 min.	B_0 max.	BS_0	$B_0(M)$	IS_i	FF	$ef\ B_0$ min.	ΔB
35	65	2700	42	1700	18	2.35	155	90
54	55	1500	27	720	24	1.15	63	8
132	44	1800	41	910	29	1.40	62	18
99	14	2100	150	1300	87	1.70	24	10
76	12.5	1800	145	720	69	2.10	26	13.5
151	11.5	1400	120	410	41	2.90	33	21.5
41	5.5	1200	220	350	80	2.75	15	9.5
59	2.0	1200	600	170	105	5.70	11.5	9.5
14	1.0	630	630	100	180	3.50	3.5	2.5
66	5.0	2600	520	570	55	9.5	48	43
Summary of All Scenes								
Min.	0.82	55	27	38	18	1.15	1.1	0.22
Max.	160	11500	750	5700	440	9.50	255	139
Av.	14.5	2300	160	640	68	2.35	34	17
Ratio	195	210	28	150	24.5	8.3	230	630

B_0 min., minimum brightness in the object;
B_0 max., maximum brightness in the object;
$B_0(M)$, integrated brightness of the object;
BS_0, brightness scale of the object;
IS_i, illumination scale of the image;
FF, flare factor;
ΔB_0, the object brightness increment equivalent to camera flare;
$ef\ B_0$ min., effective minimum brightness in the object;
$\bar{D}_n$, average density of the negative;
D min., minimum density of the negative;
D max., maximum density of the negative;
DS_n, density scale of the negative;
$h\theta_x$, highlight limiting gradient of the used portion of the negative material;
$s\theta_x$, shadow limiting gradient of the used portion of the negative material;
$h\theta_n$, highlight limiting gradient of the negative;
$s\theta_n$, shadow limiting gradient of the negative;
ϕ_x, average gradient of the used portion of the negative material;
ϕ_n, average gradient of the negative.

In Tables I and II are given the numerical values for a small group of selected scenes. These data serve simply to illustrate the general order of the values which are encountered for the various characteristics of exterior scenes and the negatives made therefrom. The summary at the bottom of Tables I and II shows maximum, minimum, and average values for the entire group of 126 scenes studied in this manner. The average value of brightness scale BS_0 is 160. This is considerably greater than was anticipated and is greater than values reported previously from these Laboratories and by other workers in this field. Also of interest is the wide variation in the value of the flare factor. It is to be remembered that all of these negatives were made with the same lens-camera assembly. Even so, the variation in flare factor is from 1.15 to 9.50, this variation being attributed entirely to variations of the distribution of brightness within the scene and its environment.

III. ADDITIONAL GROUP OF NEGATIVES

The group of scenes described in the previous communication,[1] on which brightness measurements were made, included only a few in which human figures constituted a part of the composition. Such exclusion of the outdoor portrait type of scene was for the most part intentional. The time required to make the brightness measurements, to manipulate the camera, and to record the data for any given scene is relatively long and it did not appear desirable, therefore, to employ human models in the conduct of this work. Since, however, compositions which may be described qualitatively as of the

TABLE II. Specimen data and summary. Characteristics of negatives.

Scene No.	D_n min.	D_n max.	DS_n	$\bar{D}_n$	log BS_0	$h\theta_x$	$s\theta_x$	FF	$s\theta_n$
35	0.27	0.95	0.68	0.64	1.62	0.72	0.38	2.35	0.16
54	.41	1.28	.87	.78	1.43	.80	.42	1.15	.36
132	.29	1.23	.94	.85	1.61	.71	.44	1.40	.31
99	.27	1.58	1.31	.74	2.18	.82	.40	1.70	.24
76	.70	2.10	1.40	1.38	2.16	.67	.61	2.10	.29
151	.40	1.57	1.17	.66	2.08	.76	.50	2.90	.17
41	.31	1.52	1.21	.56	2.34	.80	.38	2.75	.14
59	1.05	2.58	1.53	1.65	2.78	.55	.77	5.70	.14
14	.86	2.56	1.70	1.28	2.80	.63	.73	3.50	.21
66	.50	1.76	1.26	.79	2.72	.82	.50	9.50	.05
Summary of All Scenes									
Min.	0.11	0.95	0.68	0.56	1.43	0.52	0.20	1.15	0.05
Max.	1.08	2.90	2.23	1.65	2.88	1.00	.80	9.50	.68
Av.	.47	1.76	1.29	.93	2.20	.75	.50	2.35	.23

outdoor portrait type constitute an important class of amateur photographic activities, it seemed desirable in the present phase of the work to introduce an additional group of negatives of this type. A group of 45 such negatives was selected from a fairly large number available to represent a wide variety of compositional types describable as typical outdoor portrait negatives of the kind frequently made by amateur photographers. For this group, data relative to the brightness distributions of the scenes were not available, nor was information available as to the exact processing conditions. It was therefore impossible to establish the shape of the D_n-log B_0 characteristics for these negatives. Maximum, minimum, and average negative densities were, however, measured and from these the values of the negative density scale were computed. These values suffice for certain aspects of the problem in hand although they are not sufficient for the computation of the complete tone reproduction cycle. For some of the problems being dealt with at present, namely: (1) the establishing of the relation between the characteristics of negatives and positive materials which result in optimal photographic quality of reproduction, (2) the dependence of correct printing exposure upon characteristics of the negatives, and (3) the evaluation of the effective speed of positive materials, this additional group of negatives was entirely satisfactory. Thus, the total number of negatives available for these purposes was 171.

In Table III are given the data relative to this additional group of negatives. A comparison of the values in the summary at the bottom of the table with those in the summary of Table II shows that these negatives, in general, are very similar in density characteristics to the group representing the non-portrait scene types.

TABLE III. Density characteristics of portrait negatives.

Scene No.	D_n min.	D_n max.	DS_n	$\bar{D}_n$
1X	0.30	1.50	1.20	0.91
2X	.30	1.53	1.23	.68
3X	.25	1.55	1.30	.84
4X	.30	1.68	1.38	.78
5X	.13	1.27	1.14	.49
6X	.48	1.70	1.22	.73
7X	.37	1.45	1.08	.83
8X	.18	1.57	1.39	.79
9X	.24	1.40	1.16	.74
10X	.42	1.76	1.34	.91
11X	.34	1.50	1.16	.70
12X	.26	1.49	1.23	.85
13X	.24	1.38	1.14	.42
14X	.45	1.62	1.17	.70
15X	.46	1.74	1.28	.94
16X	.56	2.14	1.58	1.10
18X	.45	1.58	1.13	.73
19X	.42	1.72	1.30	.96
20X	.09	0.66	0.57	.24
21X	.16	1.02	.86	.42
22X	.10	.78	.68	.24
23X	.15	1.50	1.35	.48
24X	.10	.42	.32	.19
25X	.12	.50	.38	.24
27X	.16	.85	.69	.41
28X	.48	1.55	1.07	.74
29X	.68	2.50	1.82	1.30
30X	.67	1.72	1.05	1.28
31X	.73	1.81	1.08	1.31
32X	.66	1.89	1.23	1.23
33X	.59	1.73	1.14	1.17
34X	.70	1.70	1.00	1.25
36X	.42	1.77	1.35	.97
37X	.56	1.61	1.05	1.25
38X	.97	3.00	2.03	1.58
39X	.67	2.10	1.43	1.09
40X	.91	2.45	1.54	1.63
41X	.12	1.95	1.83	.64
42X	.30	1.74	1.44	.84
43X	.30	1.50	1.20	.60
46X	.19	.80	.61	.35
5116	.36	2.41	2.05	1.05
5169	.14	1.72	1.58	.30
5407	.50	2.14	1.64	1.15
5457	.20	2.32	2.12	.68
2	.95	2.14	1.19	1.48
9	.11	1.19	1.08	.45
117	.20	1.58	1.38	.59
119	.27	1.73	1.46	.79
120	.37	1.81	1.44	.71
163	.42	1.82	1.40	1.10
Min.	.09	.42	.32	.19
Max.	.97	3.00	2.12	1.63
Av.	.382	1.629	1.245	.820

IV. EXPERIMENTAL WORK

A. General Procedure

The experimental work to be presented here consists in the making of prints from the negatives discussed in the previous section, the selection of the best prints from each negative, and the measurement and computation of the relevant density and gradient characteristics of these prints. With this information available, correlations are sought between various characteristics of object, negative, positive material, and positive.

This work involves two fundamentally different techniques, namely, objective (physical)

measurements and subjective (or psychophysical) estimates or judgments.

The physical aspects of the work fall under the general headings of sensitometric and photometric and involve the making of measurements by purely physical or objective methods. The selection of a print showing a given degree of "quality," such as, first choice, second choice, etc., involves no physical measurement *per se*, but is based entirely on the operation of the observer's sensory and perceptual processes. When such a judgment is expressed in terms of the known physical characteristics of the print, the result constitutes a psychophysical datum. It is apparent, therefore, that this problem is essentially psychophysical but, since the final selection of the first-choice (or other relative quality) print depends on the average of a large number of observations which, among themselves, may spread over a considerable range, the method necessarily is statistical also.

A brief statement of the various steps involved in the experimental work may assist the reader to follow more easily the complicated and detailed discussion which must be presented in order to set forth completely and clearly all of the operations and their results. Briefly, then, the technique followed is first of all to make from a selected negative a series of prints varying in exposure on each of the several contrast grades of a selected developing-out paper. All prints are given identical treatments in development, fixing, washing, drying, etc. Along with each print is developed a sensitometrically exposed piece of the same printing material and from this sensitometric strip the density-log exposure characteristic for the positive material is obtained.

The next step is the judgment of the prints, each judge being asked to select the correctly exposed print on each of the contrast grades used and the contrast grade which yields the print of the best obtainable (first-choice) photographic quality. These decisions on correct printing exposure and best print quality should be obtained from a relatively large group of judges so that the final average values may represent as closely as possible an average opinion of the photographic public.

Measurements of maximum density, minimum density, and average density on each of the statistically selected prints are then made. This information permits the determination of the used portion of the positive material characteristic. This completes the experimental phase of the work which is followed by the establishment of significant correlations.

B. Positive Materials

A wide variety of developing-out papers is available commercially. Fundamentally these may be divided into three general groups, namely, chloride, chlorobromide, and bromide papers, depending upon the nature of the silver halide which is used in their manufacture. The chloride papers are used predominantly for contact printing, since ordinarily they do not have sufficiently high sensitivity to make them adaptable to printing in enlarging machines or projection printers. The chlorobromides are used to some extent for contact printing, but because of their greater sensitivity are well adapted to the making of projection prints. The bromide group, having in general a still greater sensitivity, is used extensively for enlarging purposes, although in some cases printing may be by contact. All of these papers are available coated on supports with surface characteristics varying from highly specular or glossy to diffusing or matte. Within any particular type, the most important variable characteristic is that designated by the term "contrast." When the photographer wishes to make a print from a given negative, he must choose a contrast grade that he thinks will "fit" the negative in question. If his first choice is not a good one, he must make another print on a more contrasty or less contrasty ("harder" or "softer") material, depending upon the appearance of his first print.

It is desirable, of course, that the result of this investigation shall be applicable to both contact and projection printing problems. The use of a projection printer, however, involves certain additional variables which it seemed wise to avoid, at least in the first stages of this investigation. For instance, some projection printers employ partially collimated light so the effective projection density of a negative is not identical with the contact printing negative density.

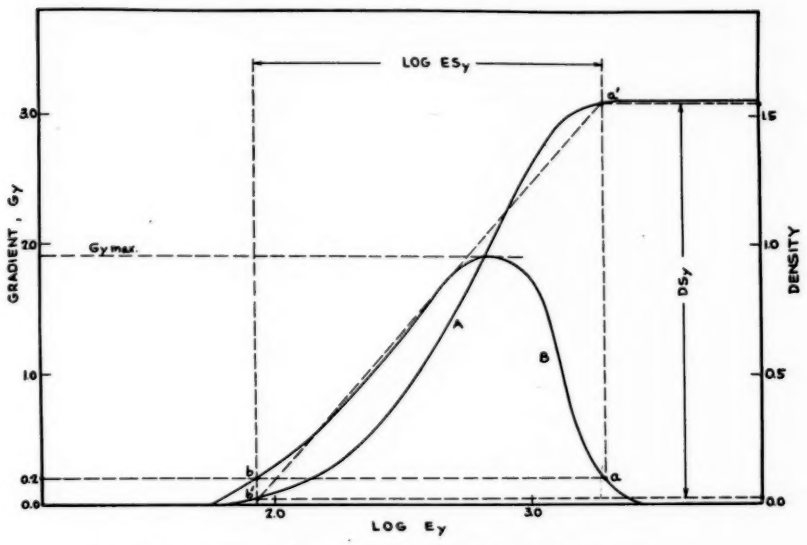

FIG. 2. Sensitometric information relative to photographic papers.

Moreover, some flare light may be present in a projection printer, with the result that the illumination incident upon the positive material is not directly proportional to the transmittance of the various areas on the negative. A third disturbing factor in some projection printers is the lack of perfect uniformity of illumination over the printing area. While this is not usually of sufficient magnitude to be of any importance in practice, it may be great enough to interfere seriously with a high precision sensitometric study, such as is involved in this work. It was decided, therefore, to employ a contact printing technique. This does not mean that the results cannot be applied to projection printing problems, since for any given projection printer it is quite possible to determine with precision its specularity and flare characteristics and to apply the necessary corrections to the sensitometric and statistical data derived from the contact printing procedure.

As stated previously, each print made from a negative was accompanied by a corresponding sensitometrically exposed strip. Hence, for each print a density-log E curve was available. For each photographic material used there was accumulated, therefore, a large number of such sensitometric curves from which a very reliable average curve was obtained which was then used in conjunction with the chosen prints of optimal quality.

Sensitometric data on developing-out papers are usually shown graphically, as illustrated by curve A in Fig. 2. The ordinates are values of density, which is defined by the following expression:

$$D = \log (1/R),$$

where R is the diffuse reflectance of the deposit in question. The abscissa values are log exposure, $\log E = \log It$, in which t is constant. Thus, the variable is the illumination I. Since for many purposes, especially in tone reproduction problems, the relation between exposure and gradient is of equal or even greater importance than the usual D-log E relationship, the first derivative of curve A is needed. This is shown in Fig. 2 as curve B, the gradient scale being at the left. The particular material represented in Fig. 2 is a No. 1 contrast grade chloride paper having a semi-matte surface. This is quite typical of the majority of developing-out papers commercially available in that the gradient increases from a zero value at very low exposure, rather gradually at first and then more rapidly, until a maximum is reached. In some cases the peak of this first derivative may be relatively broad or approxi-

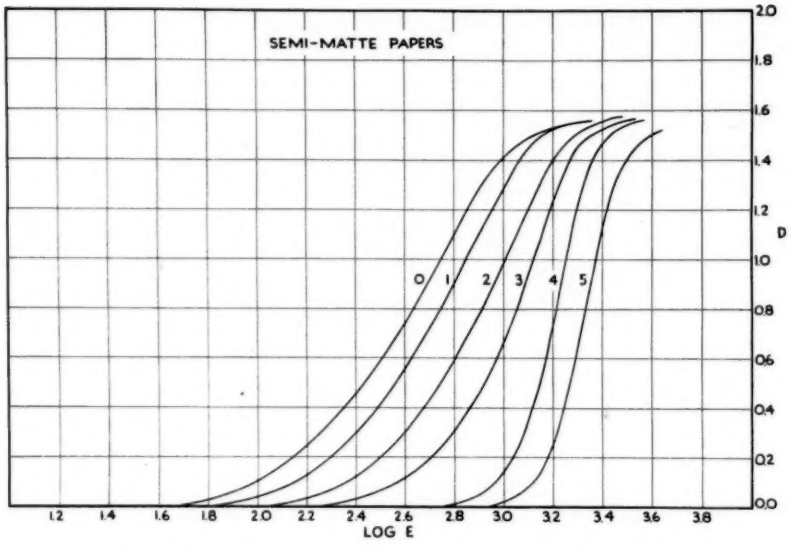

FIG. 3. *D*-log *E* characteristics for the semi-matte surface papers.

mately parallel to the log *E* axis for an appreciable exposure interval, corresponding to a part of the *D*-log *E* characteristic curve which within the limits of experimental observation is a straight line. As exposure is increased still further, the gradient usually drops rapidly to a value of zero at the point where the shoulder of the *D*-log *E* characteristic becomes parallel to the log *E* axis.

Following the printing technique already discussed, groups of prints were made from all of the 171 negatives, previously described, on a

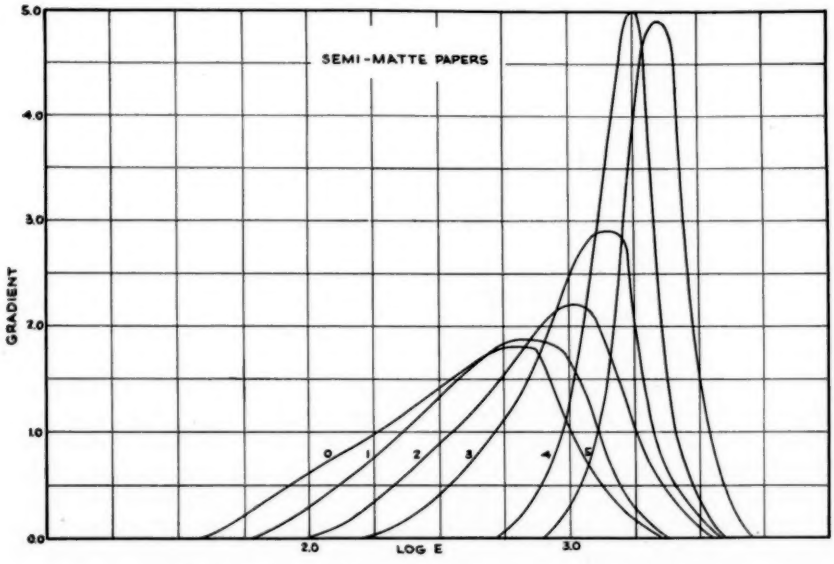

FIG. 4. First derivative curves for the semi-matte papers.

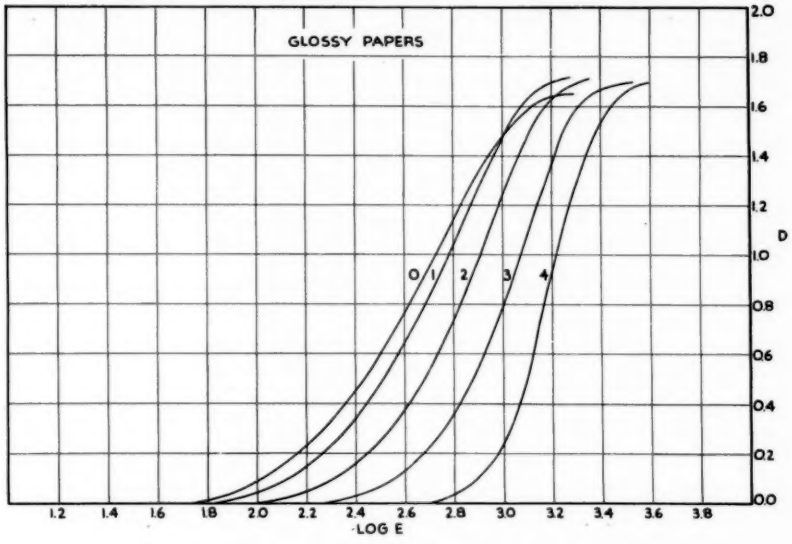

FIG. 5. Characteristic curves for the glossy surface papers.

semi-matte chloride paper, which is used extensively in the amateur photographic field. This material is available in six grades of contrast from a relatively low (No. 0) to a very high (No. 5) contrast. The D-log E characteristics for these six contrast grades are shown in Fig. 3, and in Fig. 4 will be found the first derivative curves for these same materials.

Since the surface characteristic of the paper may have some important bearing upon the relationship between positive characteristics and the chosen photographic quality, it seemed desirable to make some tests using other surfaces. For this purpose a group of 21 negatives was selected and prints from these were made on the various contrast grades, as found necessary,

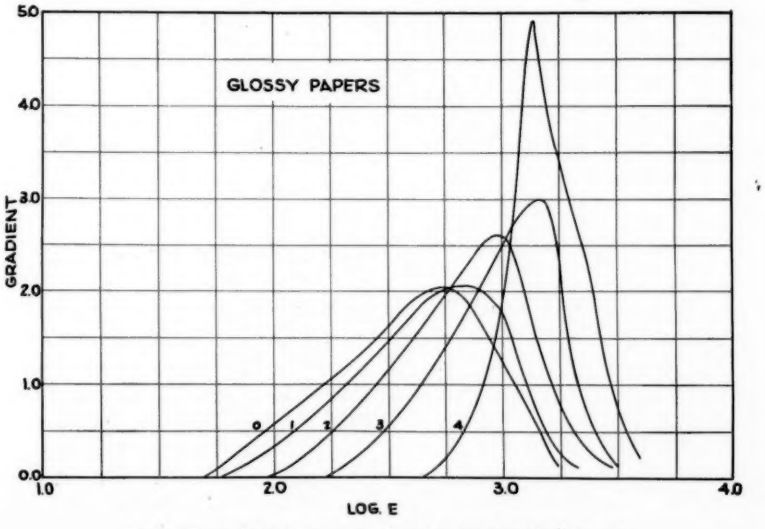

FIG. 6. First derivative curves for the glossy surface papers.

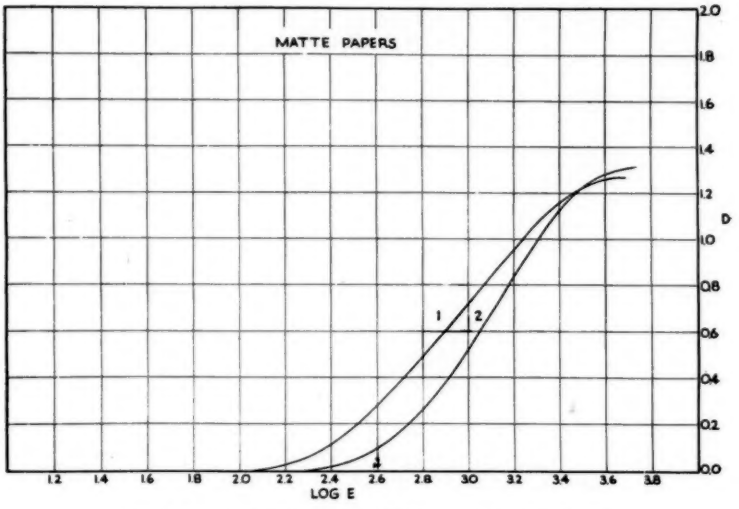

FIG. 7. Characteristic curves for the matte surface papers.

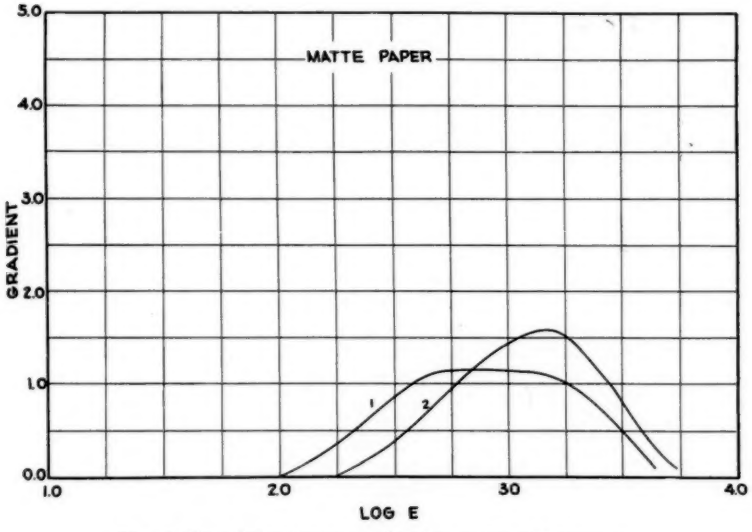

FIG. 8. First derivative curves for the matte surface papers.

of a glossy-surface chloride paper identical with the semi-matte paper previously used except for the surface. The same group was also printed on a dull matte chloride paper in which only two contrast grades were available.

The characteristic curves for the five degrees of contrast available in the glossy-surface material are shown in Fig. 5 and their corresponding first derivatives in Fig. 6. The characteristic curves and their first derivatives for matte-surface materials are shown in Figs. 7 and 8, respectively. Among the negatives a few were found for which the density scale was so great that prints made on the lowest contrast grade, No. 0, were obviously not of a quality as good as could be desired. To meet this condition an experimental developing-out paper was made having an extremely long exposure scale. This

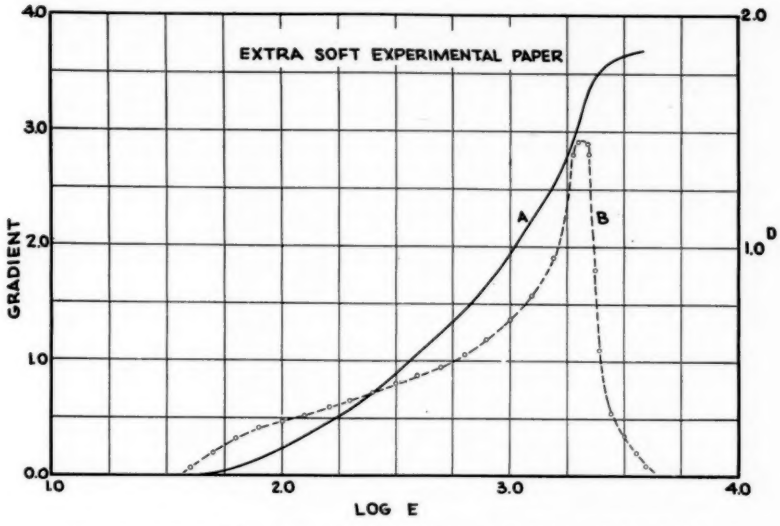

FIG. 9. Characteristic curve and first derivative for experimental material.

was obtained in a glossy surface and used in connection with those negatives from which the prints on the No. 0 contrast grade were thought to be too harsh. The entire group of prints, from a given negative, now containing a series made on the extra soft experimental material (referred to hereafter as the 00 grade) was then resubmitted for examination by the judges. In Fig. 9 the characteristic curve and its derivative for this experimental material are shown.

In Table IV the characteristics of the positive materials used are shown in numerical form. Their significance may be easily understood by reference to Fig. 2, but for more detailed information as to their significance, reference should be made to a recent communication from these Laboratories.[3] The points a and b are located on the first derivative curve where its ordinal value is 0.2. Perpendiculars from these points establish the points a' and b' on curve A. The horizontal separation between the points a' and b' gives the value of exposure scale, log ES_y, for the material, while the vertical separation gives the value of density scale DS_y. The maximum ordinate of the first derivatives gives the value of maximum gradient G max. The slope of the line connecting the points a' and b' gives the average slope of curve A between these two points. Speed is expressed in terms of the reciprocal of the exposure value corresponding to the point b'. The assumption that the total useful part of the characteristic curve lies between the limiting gradients of 0.2 is an arbitrary one and was adopted in the absence of reliable information on this point as a temporary, convenient measure of this characteristic. As will be seen later in this paper, the results of the present study make it necessary to revise drastically our concepts of the factors which determine the limits of the useful portion of the positive material charac-

TABLE IV. Sensitometric characteristics of positive materials.

Surface	Contrast grade	D max.	DS_y	ES_y	G_y max.	Log Ω	Speed
Semi-matte	0	1.56	1.52	30.2	1.80	1.61	178
	1	1.56	1.53	21.4	1.86	1.67	112
	2	1.58	1.54	18.6	2.20	1.72	66.1
	3	1.57	1.53	12.9	2.90	1.81	24.6
	4	1.56	1.54	5.36	5.00	2.03	15.8
	5	1.53	1.52	4.90	4.90	2.03	11.0
Glossy	00	1.85	1.82	69.1	2.80	1.72	200
	0	1.65	1.62	25.1	2.05	1.68	155
	1	1.72	1.69	21.9	2.05	1.78	118
	2	1.72	1.70	19.5	2.58	1.82	75.8
	3	1.70	1.67	13.2	3.00	1.86	22.4
	4	1.70	1.68	7.08	4.90	2.00	17.8
Matte	1	1.37	1.34	28.2	1.15	1.46	70.8
	2	1.31	1.29	20.0	1.57	1.53	41.7

[3] L. A. Jones and C. A. Morrison, "Sensitometry of photographic papers," J. Frank. Inst. **228**, 445, 605, 755 (1939).

teristic. However, the values in Table IV are useful as an aid to understanding the relative characteristics of the materials on which the prints were made.

C. The Variable-Intensity Contact Printer

It is important that the shape of the D-log E curve for each printing paper remain constant, even when the paper is used to print negatives which differ greatly in density. If the printing time is varied, the shape of this characteristic curve may change considerably because of the failure of the reciprocity law. To eliminate such errors, the printing time for all negatives must be kept constant and this means that the illumination on the negative during printing must be modulated to give the desired exposures.

A diagram of the special printer built for this work is shown in Fig. 10. L represents a 2000-watt, 110-volt projection type tungsten lamp. The mirror C reflects the light upward onto the ground glass D, placed in a horizontal position. The printing plane is indicated by the dotted line E, above which may be seen a representation of the platen which holds the printing paper in contact with the negative during printing. Between the light source L, and the mirror C is interposed an automatically operable shutter A and a pair of neutral gray wedges B. The two wedges at B are moved by means of a rack and pinion in vertical but opposite directions when the control knob is turned. Since the same pinion drives both wedges, it follows that they move equal distances. In this way the illumination incident upon the printing plane E can be controlled over a wide range without any appreciable change in spectral quality. A pointer attached to one of the wedges shows the position of both wedges at any instant. The scale behind this pointer is calibrated to read directly in terms of the logarithm of the illumination, log I (in metercandles), on the exposure plane of the printer. The gradient of the wedges is such that log I can be varied from 1.80 to 2.96.

A voltage regulator is used to maintain the constancy of the potential applied to the printing lamp, thus assuring constant candlepower and color temperature. A color temperature of 3000°K was chosen for this work.

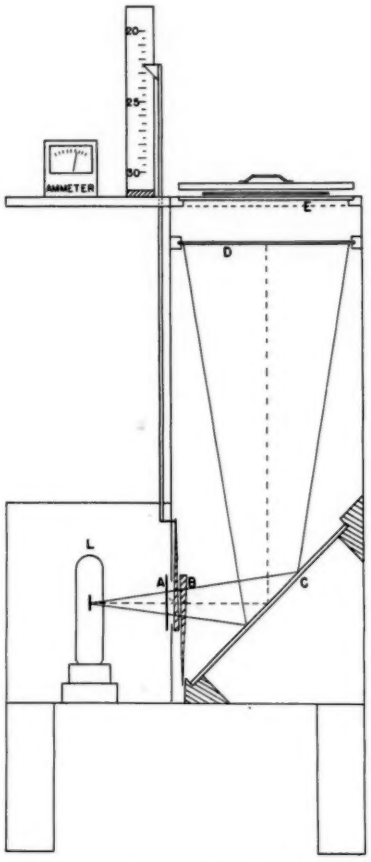

FIG. 10. Diagram of special printer.

The shutter A which is used to control the exposure time t consists of a sector wheel having two 45-degree oppositely disposed radial apertures. It is driven by a torque motor and would rotate constantly at a high angular velocity if it were not prevented from so doing by an escapement mechanism similar in principle to that found in an ordinary watch. This escapement mechanism is governed by a solenoid which is controlled by a microflex electric timer. This timer is set to operate for a fixed time interval, 10 seconds being the usual value used. When the operator presses a button on the timer, the solenoid is energized and acts on the escapement mechanism, allowing the shutter to rotate quickly through 90 degrees into its "open" position where it is stopped by an escapement

pin. At the end of the predetermined time interval the current in the solenoid is cut off by the timer and a spring pulls the escapement mechanism back to its original position, thus allowing the shutter to rotate to its "closed" position where it is again stopped by an escapement pin. The shutter is, therefore, of the high efficiency type in the sense that the time interval for the opening and closing is exceedingly short in comparison with the total exposure time. With the lamp set at the distance used in this printer and with the diffusing screen D in position, the illumination over an 8-in.×10-in. surface of the printer is exceedingly uniform. Careful photometric measurements indicate that the illumination from point to point of this area deviates from the average value by less than plus or minus 2 percent.

D. Making the Prints

Before starting to make a set of prints from a negative, the operator made a careful estimate, based upon his considerable experience in this field, of the paper contrast most likely to give a pleasing print. If it appeared that a given negative would probably be satisfactorily "fitted" by a No. 3 contrast, he made a series of prints on No. 2, No. 3, and No. 4 contrasts. If No. 1 was estimated as being the best contrast to use, the negative was printed on Nos. 0, 1, and 2. In some cases the operator's judgment was sufficiently faulty so that it was necessary to make sets of prints from a given negative on a fourth or even a fifth contrast grade. In work of this kind where judgments of print quality must be made, it is necessary, for best results, that one contrast grade which very definitely has a contrast too high to fit the negative be used, and likewise that one contrast grade which is definitely too low a contrast to fit the negative be used. Otherwise, the judge might feel a little uncertainty in making a decision as to whether a more or less contrasty grade would have yielded a print of better photographic quality than those actually placed before him on the judging board.

TABLE V. Printing exposure increments.

Paper contrast	Log exposure interval between prints
No. 0	0.12
No. 1	.10
No. 2	.08
No. 3	.06
No. 4	.04
No. 5	.04

On each of the contrast grades at least five prints were made, the printing exposure increasing by equal exposure increments from a minimum value to a maximum value. The exposure increment between successive prints in a series was so chosen that two such prints differ by two or three just noticeable (perceptible) steps in lightness (or darkness). In order that the perceptual increment in lightness between adjacent prints in a series should be the same as that in other series made with different contrast grades, it was necessary to adjust the actual exposure increment $\Delta \log E_0$, to various values, depending upon the contrast characteristic of the positive material. Thus, papers having a relatively low contrast require a larger $\Delta \log E_0$ to produce a given perceptual change in lightness than do papers having a higher contrast. For the six contrast grades used here the exposure increments required to fit the conditions just laid down are shown in Table V.

In some cases it was necessary to make more than five prints in an exposure series in order that the print of best possible quality should not fall at either of the end members of the series. Here, again, it is essential that the judge be not influenced in his final decision by not having at least one print which is definitely lighter and one print which is definitely darker than the best obtainable with this negative and contrast grade.

An exposure time of 10 seconds was used in making all of these prints, with the exception of a few cases in which the negative was so dense that longer exposure times were required at the dark end of the series. Reciprocity-law failure was thus held to a minimum; in fact, measurements indicate that no appreciable reciprocity errors can be detected in any of the prints.

The printer used proved to be ideally suited for this work as it could be set for the desired exposure time and adjusted to give the various log exposure values merely by setting the index arm of the absorbing wedges to the proper position on the log illumination scale mounted at the top of the printer. The log exposure on

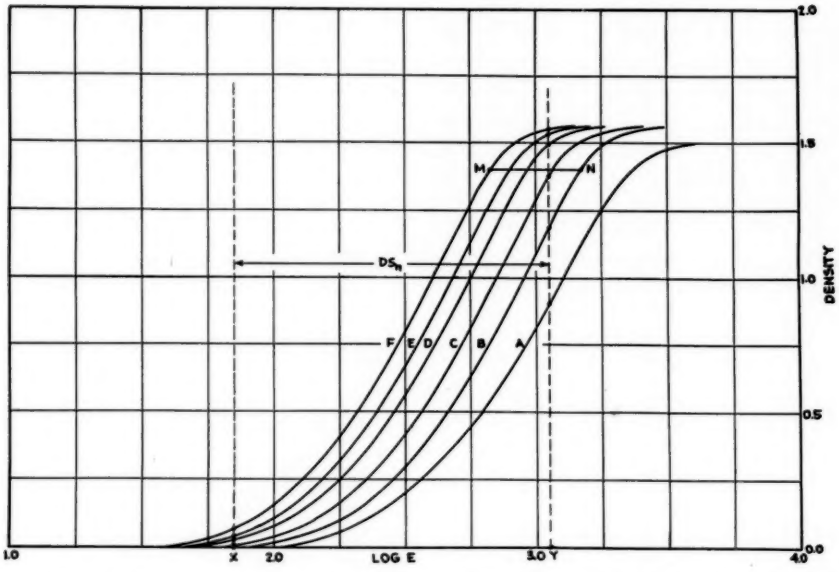

FIG. 11. Density-log E characteristic for positive material when developed under standardized processing conditions for 15, 30, 45, 60, 90, and 180 seconds.

the negative in making the print is designated as log E_0 and is obtained from the relationship

$$\log E_0 = \log I + \log t,$$

where I is the illumination on the negative, in metercandles, and t is the exposure time, in seconds. Values of log E_0 will be found in the various tables containing the numerical data.

A necessary addition to each print was the gray scale along its edge. A photographic step tablet was mounted on the exposure plane of the printer so that it always lay by the side of the negative and was printed simultaneously with it. The density values of this step tablet were measured with the same densitometer as was used in measuring the densities of the negative. This densitometer reads diffuse density which has been shown[3] to be practically identical with the effective contact printing density.

This tablet contained 30 steps of accurately known densities varying from 0.10 to 2.90. The density increment from step to step was 0.10, except in the region of the tablet which usually printed on the steepest portion of the D-log E curve of the positive material. In this region the density increment was reduced to 0.05 for the sake of greater accuracy in obtaining the true shape and position of the D-log E curve.

Before submitting the prints to the judges, these gray scales were trimmed off. If allowed to remain as a part of the print they imparted an odd, unbalanced appearance to the picture which was very distracting to most judges when they attempted to form a critical opinion of print quality. Each print was mounted on a separate heavy cardboard and its gray scale was mounted on the back of the cardboard, out of sight, yet readily available for reading on a reflection densitometer for the purpose of establishing the D-log E characteristics of the positive material.

E. Processing

In general, the development, and other operations employed in the processing of an exposed developing-out paper, are not very critical. In fact, the characteristics of a chloride paper, in particular, are such that a shortening or prolongation of a nominal development time may serve to compensate for errors of judgment made in giving the printing exposure. In this work, however, it is essential that all prints be de-

veloped to exactly the same extent, otherwise the uniformity of spacing in lightness between adjacent members of a series may be seriously disturbed. Moreover, since we wish to obtain a reliable evaluation of the relative effective printing speeds of different contrast grades of all different types of developing-out papers, it is essential that the *extent* to which development is carried be precisely controlled.

These points are of such importance that it seems desirable to illustrate them more emphatically by reference to Fig. 11 in which curves A to F, inclusive, show the density-log E characteristics for a typical positive material when developed under standardized processing conditions for 15, 30, 45, 60, 90, and 160 seconds, respectively. It will be noted that the curve obtained with 15-second development (A) is slightly less steep than curve B, and that the D max. is not quite as great as for the other members of the group. Thus, with this short time of development the curve has not attained its equilibrium shape. The remaining curves, B to F, inclusive, are identical in shape and differ only with respect to their position in the horizontal direction. Now, let a negative having a density scale, as indicated by DS_n, be printed on this material, the exposure time given being such as to place it on the log E scale of the material between the points x and y, as shown on the log E axis. It is evident that if the exposed material be developed for 15 seconds the maximum density will be very low and the minimum print density will be zero, giving the appearance of a badly underexposed print. As the development time is increased, the maximum density will rise to the various intersection points of curves A to F, inclusive, with the vertical line through y. The minimum density will rise from zero in accordance with the intersection points of these same curves, with the vertical line through x. The several prints thus obtained will have vastly different appearances. It is apparent now that the effect of varying the development time when making a print on this material is, within a certain range, equivalent to varying the printing exposure. This same condition exists to a large extent with chlorobromide and bromide papers, although the rate at which the curve shape attains equilibrium may be appreciably less than in the case of the chloride paper illustrated in Fig. 11.

Thus, for practically all commercial developing-out papers it is necessary to define precisely the extent to which development is carried in order to assign any significant speed value to the product. The specification of extent of development involves not only the constitution of the developing solution but also its temperature, degree of agitation, and the development time. The extent of development adopted in this investigation is that corresponding to curve D in Fig. 11.

It is obvious that any subsequent processing, such as fixing, washing, and drying, must be controlled within sufficiently narrow limits so that no disturbing effect will be produced.

The task of processing such a large group of prints under precisely controlled conditions was an exacting one. A total of 213 groups of prints was made. On the average, about 15 or 16 prints were made from each negative, making a total of about 3300.

The required uniformity in the extent of development was obtained by using a sensitometric developing machine.[4] In this the temperature of the developing solution is controlled precisely and the agitation is uniform and repeatable. Forty-five prints were usually put through at one time. Preliminary tests showed that without any modification of the usual agitation this machine gave a development to the photographic paper which matched very well average hand-rocked tray development carried out in accordance with ordinary trade practice.

Since all of the prints were made on 5-in.×7-in. paper, standard racks, each holding four 5-in. ×7-in. sheets, were used. Holes were punched in the corners of each print for mounting on the racks. Fresh D-72 developer diluted with two parts of water was used for all the prints. The temperature was maintained at 70°F±0.1. The prints were left on the rack during the complete process of developing, fixing, washing, and drying. They were then removed, trimmed, and dry-mounted on gray cardboard.

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[4] L. A. Jones, M. E. Russell, and H. R. Beacham, "A developing machine for sensitometric work," J. Soc. Mot. Pict. Eng. **28**, 73 (1937).

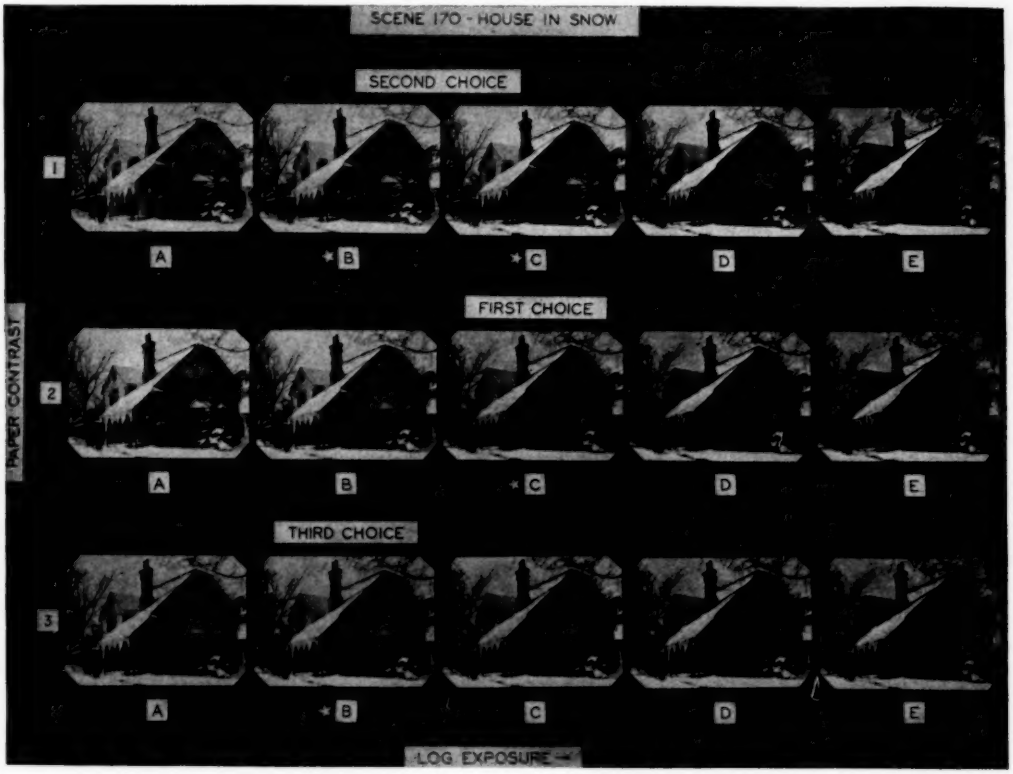

FIG. 12. Disposition of prints for judgment.

F. Judgment of Prints

We come now to a very important aspect of this work, namely, the obtaining of a large number of judgments on the relative *quality* of the prints within each of the groups. In order that the estimates of quality obtained from a group of judges shall be significant, some definite precautions must be exercised. It is well known to workers in the field of psychophysics that the conditions under which such judgments are made may profoundly influence the results.

There is little doubt that in selecting the most pleasing and best quality print from a series varying in general lightness characteristics (as a result of varying printing exposures), the illumination incident upon the prints may have an appreciable effect. A carefully designed viewing board was therefore constructed. This was so arranged that the prints were at a comfortable viewing distance from the judge and at an angle such that possible specular reflections from the illuminant produced a minimum of disturbing effect. A bank of fluorescent-daylight lamps carried in an overhead fixture provided the illumination. The illumination level of 200 foot-candles was chosen for the judging. This level is considerably above that usually encountered in viewing photographs at night, but considerably below that in well-illuminated interiors during daylight, and seems a reasonable compromise between the widely varying conditions under which photographic prints are commonly viewed.

The prints were arranged in front of the judges in three horizontal rows, each row containing the prints made on one contrast grade. The disposition of the prints for judgment is indicated in Fig. 12. In general, the rows were disposed so that the contrast of the material increased pro-

gressively from the top to the bottom. This sequence was sometimes changed purposely in order to obtain repeat judgments in substantiation of an earlier judgment. Usually, the exposure increased progressively from left to right, although, again, in some cases this order was disturbed.

In previous work of this kind it has been found, not only by us but by other workers in the field of psychophysics, that if two or more judges are permitted to examine a group of prints simultaneously they almost inevitably influence each other with regard to the choice of specified qualities. Such practice, therefore, should be avoided if the final statistical result is to have maximum significance.

No record of the contrast grade or the printing exposure was visible to the judges.

Judges were selected who did not have intimate knowledge of the technical details involved in making the prints. While some of them knew in general what was being done, actual information as to the maximum and minimum print densities and the relationships of these to the characteristic curves of the materials, the printing times, and other relevant factors, was not available to them. While some judges were used who participated in the technical part of the work, the amount of detailed numerical data involved made it quite impossible for them to remember the information relative to a particular print or set of prints with sufficient certainty so that any preconceived theories which they may have entertained as to the relationship between the relevant factors could possibly have influenced their selections of the prints of best quality.

The same instructions were given to each judge. The attendant, whose duty it was to record the judgment and the necessary data relating thereto, was careful to avoid influencing in any way the observer's judgment by any comments as to choices of previous judges, his own opinion, etc.

The judge was first instructed to select from one of the horizontal rows, for instance No. *1*, Fig. 12, the print which in his opinion exhibited the best photographic quality. As stated previously, the $\Delta \log E_0$ value between adjacent prints was such as to result in prints separated by two or three perceptible differences. In many cases, a judge, particularly if he were rather critical, found that he preferred a print intermediate in lightness between two of the actual prints, for instance, lighter than *C* but darker than *B* in row No. *1*, Fig. 12. In this case the attendant made a record of these choices as indicated by the stars placed below these two prints. The judge then chose the best print in each of the other two rows, these choices being indicated in Fig. 12 by the stars below the prints. In making these choices he was at liberty to pick up any or all of the prints and to transpose them to an order other than that in which they were originally arranged.

The judge was then instructed to choose from these three selected prints that one which in his opinion had the best photographic quality. In the case of some negatives it was exceedingly difficult for the judge to decide between two adjacent contrast grades. This of course is to be expected when we consider the sensitometric aspects of the problem. It seemed desirable, therefore, to record not only the judge's first choice, but also

TABLE VI. Judgment data for two typical scenes.

	Scene 108			Scene 29		
Judge	First choice	Second choice	Third choice	First choice	Second choice	Third choice
1	3–3.52	4–3.70	2–3.44	1–3.43	2–3.52	0–3.30
2	3–3.46	2–3.40	4–3.68	0–3.18	1–3.28	2–3.48
3	3–3.54	2–3.48	4–2.70	0–3.24	1–3.38	2–3.52
4	3–3.46	3–3.32	4–3.68	1–3.38	0–3.24	2–3.48
5	3–3.52	2–3.40	4–3.68	1–3.38	0–3.24	2–3.48
6	3–3.46	4–3.68	2–3.32	2–3.48	1–3.18	0–3.00
7	3–3.58	2–3.48	4–3.74	0–3.24	2–3.56	1–3.38
8	3–3.52	2–3.40	4–3.68	0–3.24	1–3.38	2–3.48
9	3–3.52	2–3.40	4–3.68	2–3.56	0–3.24	1–3.48
10	3–3.46	2–3.40	4–3.68	1–3.38	0–3.24	2–3.48
11	3–3.52	2–3.40	4–3.68	1–3.38	2–3.48	0–3.24
12	3–3.46	2–3.32	4–3.72	0–3.24	1–3.38	2–3.48
13	4–3.68	3–3.40	2–3.32	2–3.48	1–3.38	0–3.12
14	3–3.52	4–3.72	2–3.48	1–3.38	2–3.56	0–3.24
15	3–3.52	2–3.40	4–3.72	2–3.56	0–3.24	1–3.48
16	3–3.52	2–3.48	4–3.72	1–3.33	2–3.48	0–3.17
17	3–3.52	2–3.48	4–3.72	0–3.24	1–3.38	2–3.56
18	3–3.52	2–3.48	4–3.76	1–3.38	2–3.56	0–3.12
19	3–3.52	4–3.68	2–3.48	2–3.48	1–3.38	0–3.24
20	4–3.68	3–3.52	2–3.40	2–3.64	1–3.58	0–3.36
21	3–2.58	4–3.72	2–3.48	1–3.48	2–3.56	0–3.36
22	3–3.52	2–3.40	4–3.68	1–3.38	0–3.24	2–3.48
23	4–3.68	3–3.49	2–3.44	1–3.33	0–3.24	2–3.48
24	3–3.58	2–3.48	4–3.72	1–3.58	0–3.48	2–3.64
25	3–3.52	2–3.48	4–3.68	0–3.36	1–3.48	2–3.56
26	3–3.52	2–3.48	4–3.76	2–3.56	1–3.48	0–3.36
27	2–3.48	3–3.52	4–3.62	0–3.36	1–3.48	2–3.56
28	3–3.52	2–3.40	4–3.72	0–3.36	2–3.56	1–3.48
29	3–3.52	2–3.40	4–3.68	1–3.48	2–3.64	0–3.36
30	2–3.40	3–3.52	4–3.72	0–3.36	2–3.64	1–3.38

his second and his third. These judgments were then recorded in terms of the log printing exposure (metercandle-seconds) and the paper contrast grade, as obtained by the attendant from the data on the back of the print.

Table VI shows the results of the judgments of two scenes by thirty observers. The results are recorded in the form of a compound number, the first part of which is the contrast grade of printing paper on which the chosen print was made. The second part of the number, following the dash, is the log printing exposure, log E_0 (metercandle-seconds), incident upon the negative during the printing operation. These two characteristics of the first, second, and third choice print for each judge are shown in Table VI.

TABLE VII. Judgment data for scene No. 29.

First choice		Second choice		Third choice	
Judge	Log E_0	Judge	Log E_0	Judge	Log E_0
		Contrast Grade No. 0			
2	3.18	4	3.24	1	3.30
3	3.24	5	3.24	6	3.00
7	3.24	9	3.24	11	3.24
8	3.24	10	3.24	13	3.12
12	3.24	15	3.24	14	3.24
17	3.24	22	3.24	16	3.17
25	3.36	23	3.24	18	3.12
27	3.36	24	3.28	19	3.24
28	3.36			20	3.36
30	3.36			21	3.36
				26	3.36
				27	3.36
—	—	—	—	—	—
10	3.28	8	3.24	12	3.24
		Contrast Grade No. 1			
1	3.43	2	3.28	7	3.38
4	3.38	3	3.38	9	3.48
5	3.38	6	3.18	15	3.48
10	3.38	8	3.38	28	3.48
11	3.38	12	3.38	30	3.38
14	3.38	13	3.28		
16	3.33	17	3.38		
18	3.38	19	3.38		
21	3.48	20	3.38		
22	3.38	25	3.48		
23	3.33	26	3.48		
24	3.58	27	3.48		
29	3.48				
—	—	—	—	—	—
13	3.41	12	3.37	5	3.44
		Contrast Grade No. 2			
6	3.48	1	3.52	2	3.48
9	3.56	7	3.56	3	3.52
13	3.48	11	3.48	4	3.48
15	3.56	14	3.56	5	3.48
19	3.48	16	3.48	8	3.48
20	3.64	18	3.56	10	3.48
26	3.56	21	3.56	12	3.48
		28	3.56	17	3.56
		29	3.64	22	3.48
		30	3.64	23	3.48
				24	3.64
				25	3.56
				27	3.56
—	—	—	—	—	—
7	3.54	10	3.56	13	3.51

In closing this section it seems desirable to emphasize again the fact that the selection of a given degree of photographic quality in these prints is a purely subjective or psychical operation. It involves no knowledge whatever of the sensitometric characteristics of negative or positive materials or of the brightness characteristics of the object, of which the print is a reproduction. The observer reaches his conclusion entirely as a result of certain sensory, perceptual, and perhaps other more complicated and more highly intricate mental processes. He evaluates each of the prints in terms of his conception of the appearance of the original scene and possibly, perhaps we should say probably, chooses as first quality that print which to him appears to resemble most closely the original. In the majority of cases, of course, the judge had never actually seen the original and hence his judgment must have been based upon a vast amount of stored memory records from which he drew a conclusion as to the faithfulness with which the print reproduced the scene as he felt it must have looked.

The first step in the analysis of the judgment data is illustrated in Table VII. Here the original judgments as shown in Table VI for Scene No. 29 are classified. In the first section of the table the decisions of these thirty judges are shown relative to the quality of the best print which could be made from this negative on the No. 0 contrast grade. Thus, it will be seen that ten judges, as indicated by the code numbers used for the identification of the individual judges, in the column designated as "judge," selected the No. 0 print as first choice, eight judges selected the print made on No. 0 paper as second choice, and twelve judges gave this material third place. Likewise, in the second section of the table, contrast grade No. 1, it will be seen that thirteen judges gave this material first place, twelve gave it second place, and five gave it third place. Finally, as indicated by the third section of the table, contrast grade No. 2, we see that seven judges gave this material first place, ten gave it second, and thirteen, third place. At the bottom

TABLE VIII. Final score for scene No. 29.

Contrast grade No. 0:	(10·3)+(8·2)+(12·1)=58
Contrast grade No. 1:	(13·3)+(12·2)+(5·1)=68
Contrast grade No. 2:	(7·3)+(10·2)+(13·1)=54

of each log E_0 column of each section of the table are the average values of the printing exposure.

Now, there are several possible ways of using these data to determine which contrast grade of printing material was given first, second, and third place, with respect to photographic quality of resultant prints, by this group of judges. We have chosen to use a system commonly known as the *Hare* system for the ballots where individuals are being voted for and it is desired to place them in the correct order of preference of the voting body. The method of applying the system to this problem is illustrated in Table VIII. The total score for the No. 0 grade is computed as shown. This amounts to crediting this material with three points for each time it was chosen as first quality, two points for each time it was chosen as second quality, and one point for each time it was chosen as third quality, the sum in this case being 58. In the same manner, the No. 1 grade received 68 points, and the No. 2 grade, 54 points.

Thus, in the opinion of this group of observers, the print having the best quality was made on No. 1 contrast grade, and in the opinion of the thirteen observers who gave this material first choice, the correct exposure, log E_0, was 3.41. The average printing exposure chosen by the twelve additional observers who gave this contrast grade second place was 3.37. In arriving at the most probable correct value of printing exposure it seems reasonable to take into account the judgments of those who placed this printing material in second place, as well as the judgments of those who gave it first place. In some cases the third-choice prints were of such low photographic quality that the judgment of correct printing exposure seemed to have less significance than the judgments of this factor made on papers which gave prints of good quality. We therefore have in all cases excluded from the final value of correct printing exposure the judgments of printing exposure applying to the third-choice prints.

From the judgment data contained in Table VI and the interpretation of those data as shown in Table VII, information is finally deduced as to the first-, second-, and third-choice contrast grades and the correct printing exposure for each of the best prints made on each of these three grades of printing material from Scene No. 29. Similarly, the same information was obtained for the entire 213 groups of prints used in this investigation.

G. Measurements Made on the Positives

We now come to that part of the work dealing with the determination of certain characteristics of the prints chosen according to the technique discussed in the previous section. Some of the desired values may be obtained from measurements made on the prints, but others must be computed by use of the characteristic curves of the positive materials.

In general, the averaging of the judgment data results in a print on any given material having a printing exposure which is intermediate between two of the prints actually made. Hence, to establish the densitometric characteristics of this hypothetical print, interpolation must be resorted to. Usually, therefore, it is necessary to make measurements on two prints from each of the variable exposure series, although in some cases where the average correct printing exposure, as determined statistically, falls very close to that

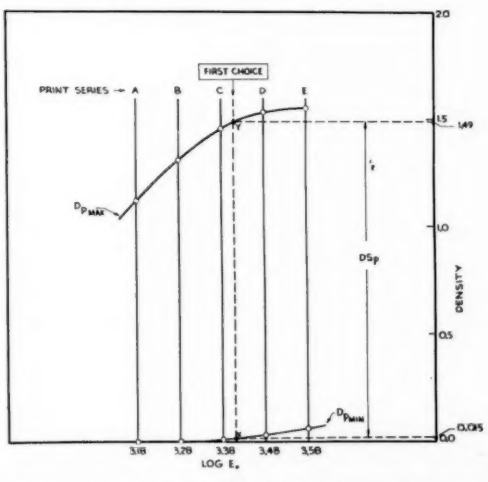

FIG. 13. Interpolation method for locating maximum print density.

TABLE IX. Characteristics of chosen positives. These are correctly exposed positives on each of three contrast grades.

Scene No.	Choice	Paper contrast grade	D_p max.	ΔD	D_p max.	D_p min.	DS_p	$\bar{G}_p$	G_p max.	$h\theta_p$	$s\theta_p$	$-\Delta h$	$-\Delta s$
5	1	1	1.56	0.06	1.50	0.02	1.48	1.20	1.86	0.2	0.7	0.00	0.0
	2	0	1.56	.16	1.40	.02	1.38	1.12	1.80	.2	1.1	.00	.0
	3	2	1.58	.06	1.52	.01	1.51	1.22	2.20	.1	0.5	.00	.0
15	1	1	1.56	.04	1.52	.00	1.52	.87	1.86	.0	.5	.38	.0
	2	2	1.58	.04	1.54	.00	1.54	.89	2.20	.0	.4	.46	.0
	3	0	1.56	.10	1.46	.00	1.46	.84	1.80	.0	.5	.36	.0
35	1	3	1.57	.23	1.34	.09	1.25	1.85	2.90	.6	2.4	.00	.0
	2	4	1.56	.19	1.37	.00	1.37	2.02	5.00	.0	2.4	.10	.0
	3	2	1.58	.47	1.11	.10	1.01	1.48	2.20	.6	2.2	.00	.0
45	1	0	1.56	.18	1.38	.00	1.38	.90	1.80	.0	1.2	.00	.0
	2	1	1.56	.05	1.51	.00	1.51	.99	1.86	.0	0.6	.19	.0
	3	2	1.58	.07	1.51	.00	1.51	.99	2.20	.0	0.6	.31	.0
65	1	2	1.58	.28	1.30	.00	1.30	.98	2.20	.0	1.8	.26	.0
	2	3	1.57	.14	1.43	.00	1.43	1.08	2.90	.0	1.6	.27	.0
	3	1	1.56	.22	1.34	.00	1.34	1.02	1.86	.0	1.6	.12	.0
75	1	0	1.56	.11	1.45	.01	1.44	1.08	1.80	.1	.9	.00	.0
	2	1	1.56	.03	1.53	.02	1.51	1.14	1.86	.2	.4	.00	.0
	3	2	1.58	.06	1.52	.01	1.51	1.14	2.20	.1	.5	.00	.0
95	1	2	1.58	.27	1.31	.005	1.31	1.20	2.20	.0	1.8	.00	.0
	2	1	1.56	.34	1.22	.01	1.21	1.10	1.86	.1	1.8	.00	.0
	3	3	1.57	.13	1.44	.01	1.43	1.32	2.90	.1	1.5	.00	.0
115	1	1	1.56	.22	1.34	.01	1.33	1.16	1.86	.1	1.6	.00	.0
	2	2	1.58	.16	1.42	.005	1.42	1.23	2.20	.0	1.3	.00	.0
	3	3	1.57	.06	1.51	.00	1.51	1.31	2.90	.0	.6	.03	.0
135	1	1	1.56	.10	1.46	.005	1.46	1.09	1.86	.0	1.1	.00	.0
	2	0	1.56	.21	1.35	.00	1.35	.99	2.20	.0	1.4	.00	.0
	3	2	1.58	.17	1.41	.00	1.41	1.06	2.90	.0	1.4	.00	.0
165	1	1	1.56	.07	1.49	.04	1.45	1.25	1.86	.3	0.8	.00	.0
	2	2	1.58	.08	1.50	.01	1.49	1.28	2.20	.1	.8	.00	.0
	3	0	1.56	.18	1.38	.03	1.35	1.12	2.90	.3	1.2	.00	.0
175	1	0	1.56	.16	1.40	.03	1.37	1.15	1.86	.3	1.1	.00	.0
	2	1	1.56	.09	1.47	.02	1.45	1.24	2.20	.2	1.0	.00	.0
	3	2	1.58	.12	1.46	.02	1.44	1.23	2.90	.2	1.0	.00	.0

of one of the actual prints, it is sufficient to make such densitometric measurements on only one print of the series.

The interpolation method is illustrated in Fig. 13. The maximum and minimum density in each of the prints made on the No. 1 contrast grade from negative No. 29 was determined. For this purpose the densitometer normally used in these Laboratories in the sensitometry of photographic papers was used. These maximum and minimum density areas correspond to the minimum and maximum negative density areas, respectively. In Fig. 13 the curve D_p max. was obtained by plotting the maximum print densities as a function of the printing exposure, log E_0. The curve D_p min. was obtained by plotting the minimum density values in the same way. The average correct printing exposure as judged by the thirteen observers, shown in the first column of Table VII, was 3.41. A perpendicular drawn through this value on the log E_0 axis locates the points x and y which give the minimum and maximum density values of this hypothetical most-correctly-exposed print. In a similar manner, the maximum and minimum print densities for the best prints on the second- and third-choice printing materials were determined. The difference between D_p max. and D_p min. gives the density scale DS_p of the print. These values as determined for several typical scenes, indicated by the numbers in the first column, are shown in Table IX in the appropriate columns. From measurements made on

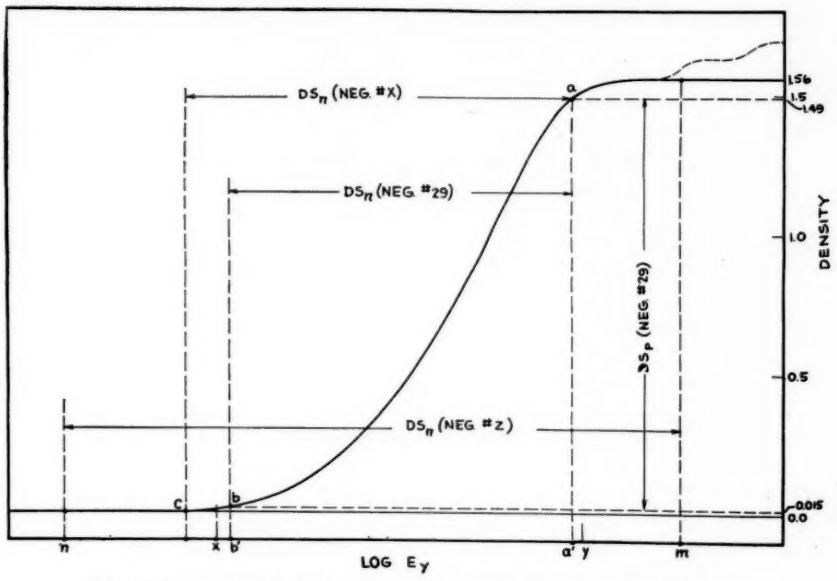

FIG. 14. Method used in isolating the used portion of the characteristic curve.

the print, the following values are obtained:

D_p max., maximum print density;
D_p min., minimum print density;
DS_p, density scale of the print
$= D_p$ max. $- D_p$ min.

H. Isolation of the Used Portion of the Positive Material Characteristic Curve

The next step in the analysis of these results is the isolation of that part of the characteristic curve of the positive material which was used in making each of the best prints on the various contrast grades of printing material. For this purpose it was desirable to establish with a high degree of precision the shape of the D-log E_y characteristic for each of the positive materials. The intensity-scale sensitometric strips made with each print were measured in the usual manner and thus a large number of determinations of the D-log E_y characteristic were obtained for all of the contrast grades used. An average curve derived from these voluminous data was plotted on suitable coordinate paper and from this a sufficient number of photographic reproductions were made so that each first-, second-, and third-choice print could be plotted on its appropriate characteristic curve.

The method used in isolating the used portion of the characteristic curve is illustrated in Fig. 14. The curve is the average characteristic curve for the No. 1 contrast grade of the semi-matte material. It rises from a value of zero density to a maximum density of 1.56, beyond which, as shown, the curve runs parallel to the log E axis. As a matter of fact, all photographic materials generally show some additional rise in density as indicated approximately by the dotted line, this portion being known as the "extra shoulder." This has been discussed at length in a previous communication[3] and, as stated there, this additional density is of no use for the reproduction of density differences in the negative, and hence, from the standpoint of the present work, may be neglected. The evidence to be presented later in this paper strongly supports this conclusion.

In the case of scene No. 29 the isolation of the used portion is a relatively simple problem. The maximum density of the first-choice print of this scene is 1.49, while the minimum is 0.015. A horizontal line drawn at a density of 1.49 establishes a point a, while a second horizontal line drawn at a density of 0.015 establishes the point b. Thus, on the basis of the evidence derived from the chosen print, the used portion of the characteristic curve lies between these two points.

An inspection of the data in Table IX shows that in many cases the minimum density is zero. Hence, in these cases the position of the point b becomes indeterminate. Even in the case of scene No. 29, since the minimum print density is very low, 0.015, it is evident that the determination of the minimum exposure incident upon the photographic material is subject to a large uncertainty because the slope of the characteristic curve at this density value is very low and a small error in the determination of D_p min., for instance, ± 0.01, would produce a large uncertainty in the value of the minimum exposure.

There is, of course, another method which may be employed to locate the used portion of the characteristic curve. The printing exposure for each of the chosen prints is known and the maximum and minimum negative density is known. Hence, we may compute the exposure incident upon the photographic material under the areas of the negative having maximum and minimum density. If this is done in the case of the negative of scene No. 29, the points x and y are established. These do not agree perfectly with the exposure values corresponding to the points a and b and these discrepancies represent the magnitude of experimental errors in the entire chain of measurements and operations involved.

In general, these discrepancies are relatively small. The magnitude of the departure in any case can be expressed in terms of $\Delta \log E$ which is obtained by taking the difference between the $\log E_y$ at the point y and the $\log E_y$ at the point a'. In some cases this $\Delta \log E$ is positive and in other cases, negative. The average $\Delta \log E$ derived from 695 correctly exposed prints is $+0.03$. At the highlight end of the tonal scale the corresponding average $\Delta \log E$ value is somewhat greater, being -0.05. This is to be expected since the minimum print density usually falls on the characteristic curve where its gradient is very low, while the maximum print density falls at the place where the gradient is relatively high.

If all values of D_p min. were greater than zero, the best procedure to follow in isolating the used portion of the characteristic curve might be to take an average between the results obtained from the use of maximum and minimum print densities and those resulting from computation from the maximum and minimum negative densities. However, it has been found that in more than one-half of the cases the minimum print density is zero; thus it is impossible to apply this method in all cases.

On the other hand, in the shadow region of the tonal scale it is found that the maximum print density in no case is equal to the maximum density of the positive material and, as will be seen by reference to Table IX, this maximum print density is usually considerably below the maximum density of the positive material. This means that the location of the point a, as illustrated in Fig. 14, determines the maximum exposure incident on the positive material with considerable precision. Since, in the selection of the correctly exposed print, the judgment was based upon the appearance of the print, one aspect of which, of course, is its maximum density and the perfection of the rendition of shadow detail, we consider the best practice in locating the limit of the used portion of the characteristic curve in the shadow region to be the use of the measured maximum print density, as illustrated by point a in Fig. 14. Now, by measuring to the left from this point a distance equal to the density scale of the negative, the value of the minimum exposure incident on the positive material may be determined. This is illustrated for a hypothetical negative No. X, in which case the minimum exposure is determined by the location of point c.

It is of course possible that cases may be found where the maximum print density is equal to the maximum density of the positive material and the minimum density zero. Under such conditions we are forced to resort to computation from the known incident printing exposure. Such a case is illustrated for a hypothetical negative No. Z by the location of the points m and n. This can occur only when the density scale of the negative is greater than the total exposure scale of the positive material. When this condition exists, the resultant positive shows no detail in the extreme highlight and shadow regions and these portions of the tonal scale of the object are completely lost. No case in which maximum print density was equal to the maximum density of the positive material was found. This means that in no case of a chosen print was any part of the tonal scale of the object in the shadow region rendered with-

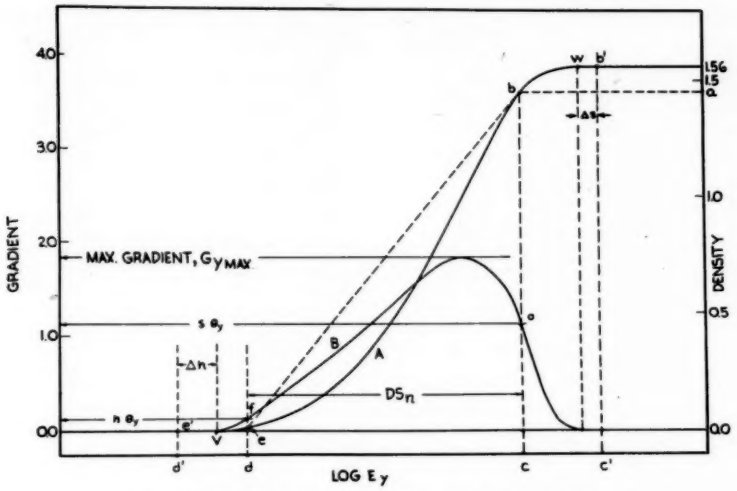

FIG. 15. Method of obtaining the derived sensitometric data.

out some detail, although this detail in many cases suffered considerable compression. On the other hand, many cases occurred in which the minimum print density was zero and in some cases appreciable portions of the tonal scale of the object in the highlight region were rendered with complete loss of detail.

I. Computed and Derived Values

In Fig. 15 the method of obtaining the derived values is illustrated. The point a is located on the density scale at the value of D_p max., measured on a single chosen print or interpolated between two such measurements if necessary. A horizontal line through a locates b on the characteristic curve. A perpendicular dropped to the log E_y axis locates the point c, giving log E_y max. The density scale of the negative DS_n, from which the print was made, determined the separation between points c and d, the position of point d giving log E_y min. A perpendicular through d locates e on the characteristic curve, thus giving D_p min.

Curve B (Fig. 15) is the first derivative of A, thus showing values of gradient, $G = dD/d \log E$, as a function of log E_y. A perpendicular through the point d intersects curve B at the point f. A horizontal through this point to the gradient scale (at the left) gives the value of $h\theta_y$, the *limiting gradient* of the used portion of the characteristic curve of the positive material in the *highlight* region. Likewise, a perpendicular through c establishes point o, the ordinate of which gives $s\theta_y$, the *limiting gradient* of the used portion of the characteristic curve of the positive material in the *shadow* region. The slope of the line eb gives the average gradient $\bar{G}_y$ of the used portion of the characteristic curve. A horizontal line drawn tangent to the top of curve B gives the maximum gradient G_y max. of curve A. This gradient obviously gives the slope of curve A at its inflection point or for that part, usually small, of A which may be a straight line.

The points v and w are located on the log E_y scale where the slope of the characteristic curve is 0.00. It is difficult to measure precisely gradients less than about 0.05, but by extrapolation from values of easily measurable magnitude the positions of points v and w can be located with reasonable exactness. The log E_y interval between points v and w gives the value of the total available exposure scale. Care should be exercised to distinguish between this aspect of exposure scale and that of the *useful* exposure scale, which we shall discuss in some detail at a later time.

It is evident that the maximum exposure incident upon the positive material may be either greater or less than the exposure corresponding to the point w. Likewise, it may happen that the

minimum exposure incident on the positive material is either greater or less than the exposure corresponding to the point v. We may now define two terms used in indicating the extent to which the *total available* exposure scale of the positive material or the total tonal scale of the negative is utilized. The first of these is:

$$\Delta s = \log E_y \text{ (at point } w) - \log E_y \text{ max.}$$

It is evident that Δs may be either negative or positive.

If it is negative, it becomes a measure of the part of the negative tonal scale in the extreme shadow region which is *discarded* in making the print, and is also a measure, in case the negative characteristic is known, of that part of the tonal scale of the scene in the shadow region which is rendered with complete loss of detail in this positive.

In case Δs is positive, it becomes a measure of that part of the available exposure scale of the positive material which is not utilized in making the print and if desired can be converted into the equivalent part of the density scale of the paper which is discarded.

The second term is Δh.

$$\Delta h = \log E_y \text{ min.} - \log E_y \text{ (at the point } v).$$

It is evident that Δh may also be either negative or positive.

If Δh is negative, it becomes a measure of the part of the negative tonal scale in the extreme highlight region which is *discarded* in making the print, and is also a measure, in case the negative characteristic is known, of the magnitude of that part of the tonal scale of the scene in the highlight region which is rendered with complete loss of detail in the positive.

If Δh is positive, it becomes a measure of the part of the total available exposure scale of the positive materials which is not utilized in making the print and if desired can be converted into the equivalent part of the density scale of the paper which is not utilized.

No case has been found among the 213 groups of prints thus far judged in either the first-, second-, or third-choice prints where Δs has a negative value, although in many cases it has an appreciable positive value. On the other hand, many cases have been noted where Δh is negative, indicating that frequently a portion of the negative tonal scale in the highlight region is not utilized in making the positive; in fact, cases have been noted where its value is -0.55.

There is one other value of interest which is not derived directly from the graphical construction shown in Fig. 15, but from the value of the incident printing exposure $\log E_0$ and the average negative density. This is the average exposure incident on the positive material during printing, $\log \bar{E}_y$.

$$\log \bar{E}_y = \log E_0 - \bar{D}_n.$$

We may now summarize the values derived from these constructional and computational operations.

Summary of Computed Values

$\log E_y$ max., the maximum exposure incident upon the positive material.

$\log E_y$ min., the minimum exposure incident upon the positive material.

$\log E_y$ min. $= \log E_y$ max. $- DS_n$.

$\log \bar{E}_y = \log E_0 - \bar{D}_n$.

$\bar{G}_y$, the average gradient of the used part of the positive characteristic.

G_y max., the maximum gradient of the positive material characteristic.

$h\theta_y$, the limiting gradient at the highlight end of the used part of the positive characteristic curve.

$s\theta_y$, the limiting gradient at the shadow end of the used part of the positive characteristic curve.

$-\Delta h$, the discarded part of the negative tonal scale in the highlight region.

$-\Delta s$, the discarded part of the negative tonal scale in the shadow region.

It seems inadvisable, because of the additional space required, to publish the measured and computed values for all of the 213 print groups which have been examined. As illustrative of the form which these data take, values for a few selected groups of prints are shown in Table IX. This represents a fair cross section of the data relative to the chosen prints.

It is of interest to consider a few significant aspects of these data. In column ΔD are tabulated values obtained by subtracting the maxi-

TABLE X. Complete summary of data pertaining to scene 175.

	Characteristics of the scene			
B_0 max.	Maximum object brightness (ft.-L)	3000		
B_0 min.	Minimum object brightness (ft.-L)	17		
BS_0	Brightness scale of the object	175		
$B_0(M)$	Integrated brightness of the object (ft.-L)	1000		
	Exposure conditions			
S	Speed of the negative material, $1/E$ at $0.3\bar{G}$	160		
f	Aperture ratio	11		
t	Exposure time (seconds)	1/15		
	Characteristics of the camera image			
I_i max.	Maximum image illumination (mc)	57		
I_i min.	Minimum image illumination (mc)	1.1		
IS_i	Illumination scale	51		
FF	Flare factor	3.4		
I_f	Flare illumination (mc)	0.78		
	Characteristics of the negative			
D_n max.	Maximum negative density	1.55		
D_n min.	Minimum negative density	0.37		
DS_n	Density scale of the negative	1.18		
$\bar{D}_n$	Average density of the negative	0.87		
$\bar{G}_x$	Average gradient of used portion of the negative material	0.69		
$\bar{G}_n$	Average gradient of the negative	0.53		
$h\theta_x$	Highlight limiting gradient for used portion of negative material	0.75		
$s\theta_x$	Shadow limiting gradient for used portion of negative material	0.48		
$h\theta_n$	Highlight limiting gradient for used portion of negative	0.75		
$s\theta_n$	Shadow limiting gradient for used portion of negative	0.14		
	Printing Conditions	First-choice print	Second-choice print	Third-choice print
I_n	Illumination on the negative (mc)	219	302	427
t	Exposure time (seconds)	10	10	10
I_y max.	Maximum illumination on positive material (mc)	94	130	183
I_y min.	Minimum illumination on positive material (mc)	15	20	29
	Characteristics of the Positives			
D_y max.	Maximum density of the positive material	1.56	1.56	1.58
D_p max.	Maximum density of the print	1.40	1.47	1.46
D_p min.	Minimum density of the print	0.03	0.02	0.02
DS_p	Density scale of the print	1.37	1.45	1.44
$h\theta_y$	Highlight limiting gradient for used portion of the positive material	0.3	0.1	0.1
$s\theta_y$	Shadow limiting gradient for used portion of the positive material	1.1	1.0	1.0
$\bar{G}_y$	Average gradient for used portion of the positive material	1.15	1.24	1.22
G_y max.	Maximum gradient for used portion of the positive material	1.80	1.86	2.20
	Characteristics of the Reproductions			
B_r max.	Maximum brightness of the reproduction (ft.-L)	148.0	152.0	152.0
B_r min.	Minimum brightness of the reproduction (ft.-L)	6.3	5.4	5.5
BS_r	Brightness scale of the reproduction	23.4	28.2	27.7
BS_0	Brightness scale of the scene	175.0	175.0	175.0
$\bar{G}_r$	Average gradient of the reproduction	0.61	0.65	0.64
G_r max.	Maximum gradient of the reproduction	0.97	1.11	1.48
$h\theta_r$	Highlight limiting gradient of the reproduction	0.22	0.07	0.07
$s\theta_r$	Shadow limiting gradient of the reproduction	0.15	0.14	0.14

mum print density from the maximum density of the positive material. It will be seen that these values are always greater than 0.0 and in some cases quite large, showing that the best possible print that can be made on the contrast grade of paper designated has a maximum density below that which is available. Values of minimum density D_p min. are, in general, low and often zero. Values of limiting gradient $h\theta_y$ at the highlight end of the used portion of the positive material characteristic curve are quite low and in many cases zero. On the other hand, the values of limiting gradient at the shadow end of the tonal scale $s\theta_y$ are quite high. There seems to be a

tendency for $s\theta_y$ to be fairly constant for the best prints from a given negative made on each of the three contrast grades. This correlation is not high, but is considered significant and an indication that this limiting gradient is determined by the characteristics of the negative and those of the scene. Values of $-\Delta h$, the discarded portion of the highlight negative tonal scale, are in some cases quite large and here again seem to be dependent upon the characteristic of the negative and the scene rather than of the positive material. Values of $-\Delta s$, the discarded portion of the negative tonal scale in the shadow region, are in *all* cases zero.

A summary may now be made of all the data pertaining to one scene and the negative and the chosen positives (first, second, and third choice). Table X is such a summary for scene 175, and is one of 213 such tables.

Scene 175 had a relatively high brightness contrast, 175. Because of camera flare the ratio of maximum to minimum illumination incident on the negative material IS_i was reduced to 51. The resultant negative had a density scale of 1.18 with a fairly high limiting gradient in the highlight region, $h\theta_n = 0.75$, and a rather low limiting gradient at the shadow end, $s\theta_n = 0.14$.

From the section in which are given the data relative to the chosen positives it will be seen that the first-choice print, which was made on the No. 0 contrast grade, has a lower D max. than either the second- or third-choice prints, in all cases, the D max. being appreciably below the available D max. of the positive material. The limiting gradients of the used portion of the positive characteristic curve are relatively high at the shadow end and relatively low at the highlight end, the first-choice print showing a somewhat higher value of this factor than the other two. In the last section of the table are shown the computed characteristics of the reproductions, these being the prints as viewed under an illumination of 200 footcandles. In general, the values for the first-choice print do not differ very much from those applying to the second- and third-choice prints. However, in the case of the first-choice print, the limiting gradients $s\theta_r$ and $h\theta_r$ are higher relative to that maximum gradient, G_r max. This means that the reproduction curve for the first-choice print approximates more closely a straight line than those for the second- and third-choice prints. This condition seems to be a general one and we feel there is little doubt that print quality in practically all cases depends upon reducing departure from straight-line reproduction to a minimum.

V. ANALYSIS OF RESULTS AND ESTABLISHMENT OF CORRELATIONS

Before beginning the detailed discussion of this section it is advisable to draw attention to certain limitations which must be imposed upon conclusions drawn from the data accumulated in this work.

The majority of the negatives used resulted from *normal* exposure. As used here, the term normal exposure serves to exclude *underexposure* and *overexposure*. If the lowest brightness in an object is rendered by a density in the negative which is not greater than the fog density for the negative material with the processing condition employed, the negative is said to be *underexposed*. If the highest brightness in the scene is rendered by a density on the shoulder of the characteristic curve where the gradient is less than one-half of that of the maximum gradient of the negative material, gamma, the negative is considered to be overexposed. Any conclusions drawn from the use of these accumulated data, therefore, may not necessarily apply to negatives which, in terms of the above definitions, are over- or underexposed.

All the negatives used in this work received normal development. That is, they were developed according to the recommendations of the manufacturer with respect to developer, temperature, and time. For this group of negatives, gamma varies from 0.70 to 1.00, with the majority of values deviating but little from the average, 0.80. Conclusions drawn from these data are therefore not necessarily applicable to negatives which have been over- or underdeveloped.

We shall now proceed with the application of the available data to the following problems:

Criteria of correct printing exposure.
Criteria for correct contrast grade.
Significance of these results for the sensitometry of developing-out papers.
Tone reproduction quality and its controlling factors.

A. Classification of Scene Types

It should not be assumed without supporting evidence that the brightness and compositional characteristics of the scene have no influence on the criterion of correct printing exposure and the criterion for selecting the contrast grade which will yield a print of best possible quality. It is desirable, therefore, if possible to classify the scenes into groups exhibiting maximal homogeneity with respect to certain brightness and compositional (structural) characteristics.

In a previous communication from these Laboratories[1] considerable attention was devoted to the formulation of a rational system of classifying exterior scenes according to their brightness characteristics. This system is based upon variations in four relevant factors, namely:

A. General illumination conditions
   1. Sun unobscured
   2. Sun obscured by haze
   3. Sun obscured by light clouds
   4. Sun obscured by heavy clouds

B. Directional illumination aspects
   1. Front lighting
   2. Side lighting
   3. Back lighting

C. Spatial distribution of scene elements (structural)
   1. Distant
   2. Remote (semi-distant)
   3. Nearby
   4. Close-up

D. Local illumination conditions
   1. Unshaded
   2. Light shade
   3. Heavy shade.

We shall not present a comprehensive discussion of this classification system in this communication. For this the reader is referred to the paper in which it was first set forth[1] and to a later one[5] in which a further elaboration of the system and additional evidence as to its soundness and rationality is given.

By using this method of classifying exterior scenes according to the type of illumination and structural characteristics, it was shown that the groups thus formed are sufficiently homogeneous with respect to minimum brightness so that the average B_0 min. for a group is a reliable guide for computing the correct exposure in making a negative of any member of the group.

[5] L. A. Jones and H. R. Condit, to be published,

For the present purpose the same classification system will be used with the addition of one group composed exclusively of scenes of the exterior portrait type.

It has been contended by some workers in this field that in scenes of the non-portrait type the interest of the observer is not in general centered on any particular part of the tonal scale, while in portrait-type scenes, interest is always centered on a very definite part of the tonal scale, namely, that occupied by the flesh tones and clothing of the model. Hence it has been argued that it is not to be expected that the criterion of correct printing exposure or the criterion for the choice of the best possible contrast grade of positive material will necessarily be the same for these two distinct scene types. To test this point, the group of portrait negatives was added.

An inspection of the scenes used in this work shows that all are *front-lighted*. They may be classified into a few groups, as follows:

Group I: number of cases, 28; non-portrait; distant; sun unobscured.

Group II: Number of cases, 39; non-portrait; semi-distant (remote); sun unobscured.

Group III: number of cases, 37; non-portrait; near; sun unobscured; unshaded.

Group III-P: number of cases, 36; portrait; near and close; sun unobscured; unshaded and light shade.

Group IV: number of cases, 20; non-portrait; close; sun unobscured; unshaded and shaded.

Group V: Number of cases, 21; non-portrait; distant, semi-distant, and near; haze, light clouds, and heavy clouds.

Group V-P: number of cases, 15; portrait; near and close; haze, light clouds, heavy clouds; unshaded and light shade.

The next step involves the collection of all the data relative to the first-choice prints into one systematic tabulation, those pertaining to the second-choice prints into another, and those for the third-choice prints into a third. One such tabulation is made for each of the groups of scene types discussed in the preceding pages, the values for the prints made on each contrast grade being grouped together and averaged.

Table XI is one of the 21 required to accommodate all the data now accumulated. These data pertain to the first-choice prints of Group II scenes. It will be noted that the average value of negative density scale decreases progressively as the contrast of the printing paper increases.

TABLE XI. Group II scenes. Characteristics of negatives and first-choice prints.

Scene		Negative data				Positive data												
Scene No	BS_0	D_n min.	D_n max.	DS_n	$\bar{D}_n$	D_p max.	D_p min.	DS_p	Log E_0	Log E_y max.	Log E_y min.	Log $\bar{E}_y$	$s\theta_y$	$h\theta_y$	$\bar{G}_y$	G_y max.	$-\Delta h$	$-\Delta s$
						Glossy paper 00 (D_y max. = 1.85)												
46	2.47	0.30	2.12	1.82	1.00	1.78	0.00	1.78	3.66	3.42	1.60	2.66	1.0	0.0	0.97	2.85	0.00	0.00
						Semi-matte paper 0 (D_y max. = 1.56)												
29	2.29	0.24	1.58	1.34	0.78	1.40	0.01	1.39	3.31	3.00	1.60	2.53	1.1	0.0	1.03	1.80	0.00	0.00
78	2.39	0.40	1.82	1.42	0.82	1.41	0.00	1.41	3.46	3.00	1.58	2.64	1.0	0.0	0.98	1.80	0.08	0.00
146	2.11	0.29	1.50	1.21	0.64	1.40	0.02	1.38	3.24	3.00	1.78	2.60	1.1	0.2	1.11	1.80	0.00	0.00
156	2.53	0.46	1.84	1.38	0.76	1.33	0.00	1.33	3.36	2.94	1.56	2.60	1.5	0.0	0.96	1.80	0.12	0.00
168	2.28	0.44	1.78	1.34	1.00	1.44	0.01	1.43	3.53	3.03	1.69	2.53	0.9	0.1	1.04	1.80	0.00	0.00
Avg.	2.32	0.37	1.70	1.34	0.80	1.40	0.01	1.39	3.38	2.99	1.64	2.58	1.1	0.1	1.02	1.80	0.02	0.00
						Semi-matte paper 1 (D_y max. = 1.56)												
5	2.29	0.40	1.63	1.23	0.97	1.50	0.02	1.48	3.57	3.16	1.93	2.60	0.7	0.2	1.20	1.86	0.00	0.00
38	2.45	0.21	1.54	1.33	0.70	1.37	0.00	1.37	3.24	3.04	1.71	2.54	1.5	0.0	1.03	1.86	0.12	0.00
60	2.39	0.62	2.16	1.54	1.43	1.52	0.00	1.52	3.92	3.19	1.65	2.49	0.5	0.0	0.99	1.86	0.18	0.00
99	2.18	0.27	1.58	1.31	0.74	1.49	0.01	1.48	3.43	3.14	1.83	2.69	0.8	0.1	1.13	1.86	0.00	0.00
104	2.08	0.34	1.47	1.13	0.70	1.40	0.02	1.38	3.40	3.06	1.93	2.70	1.4	0.2	1.21	1.86	0.00	0.00
115	1.98	0.52	1.67	1.15	1.10	1.34	0.01	1.33	3.49	3.03	1.88	2.39	1.6	0.1	1.16	1.86	0.00	0.00
116	2.13	0.36	1.64	1.28	0.77	1.51	0.01	1.50	3.57	3.17	1.89	2.80	0.6	0.1	1.15	1.86	0.00	0.00
135	2.51	0.43	1.75	1.32	0.90	1.46	0.01	1.45	3.49	3.11	1.79	2.59	1.1	0.0	1.09	1.86	0.00	0.00
136	2.26	0.38	1.65	1.27	0.84	1.38	0.00	1.38	3.47	3.05	1.78	2.63	1.5	0.0	1.07	1.86	0.00	0.00
138	2.16	0.28	1.30	1.02	0.67	1.45	0.07	1.38	3.52	3.10	2.08	2.85	1.2	0.5	1.36	1.86	0.00	0.00
139	2.15	0.55	1.76	1.21	1.06	1.42	0.01	1.41	3.62	3.08	1.87	2.56	1.3	0.1	1.16	1.86	0.00	0.00
141	2.33	0.40	1.66	1.26	1.12	1.50	0.01	1.49	3.62	3.16	1.90	2.50	0.7	0.1	1.16	1.86	0.00	0.00
144	1.76	0.45	1.64	1.19	1.06	1.50	0.04	1.46	3.58	3.16	1.97	2.52	0.5	0.3	1.26	1.86	0.00	0.00
147	2.16	0.55	1.74	1.19	1.15	1.50	0.03	1.47	3.71	3.16	1.97	2.56	0.7	0.3	1.19	1.86	0.00	0.00
158	1.95	0.80	1.95	1.15	1.30	1.48	0.03	1.45	4.00	3.14	1.99	2.70	0.9	0.3	1.22	1.86	0.00	0.00
162	2.30	0.38	1.53	1.15	0.75	1.44	0.02	1.42	3.49	3.10	1.95	2.74	1.2	0.2	1.21	1.86	0.00	0.00
164	2.26	0.36	1.69	1.33	0.73	1.47	0.01	1.47	3.47	3.12	1.79	2.74	1.0	0.1	1.10	1.86	0.00	0.00
165	2.35	0.38	1.53	1.15	0.88	1.49	0.04	1.45	3.48	3.14	1.99	2.60	0.8	0.3	1.25	1.86	0.00	0.00
166	2.24	0.47	1.79	1.32	0.81	1.41	0.00	1.41	3.57	3.07	1.75	3.76	1.3	0.0	1.07	1.86	0.06	0.00
172	2.26	0.40	1.68	1.28	1.15	1.50	0.01	1.49	3.62	3.16	1.88	2.47	0.7	0.1	1.16	1.86	0.00	0.00
Avg.	2.21	0.43	1.67	1.24	0.94	1.46	0.02	1.44	3.56	3.12	1.88	2.62	1.0	0.1	1.16	1.86	0.02	0.00
						Semi-matte paper 2 (D_y max. = 1.58)												
51	1.72	0.66	1.70	1.04	1.00	1.22	0.00	1.22	3.75	3.10	2.06	2.75	2.0	0.0	1.17	2.20	0.00	0.00
53	1.96	0.68	1.78	1.10	1.30	1.48	0.02	1.46	4.00	3.14	2.04	2.70	0.9	0.2	1.27	2.20	0.00	0.00
95	2.06	0.42	1.50	1.08	0.76	1.31	0.01	1.30	3.55	3.15	2.07	2.79	1.8	0.1	1.20	2.20	0.00	0.00
96	1.81	0.42	1.72	1.30	0.91	1.46	0.00	1.46	3.65	3.24	1.94	2.74	1.0	0.0	1.11	2.20	0.09	0.00
123	2.10	0.33	1.30	0.97	0.70	1.35	0.03	1.32	3.43	3.17	2.20	2.73	1.6	0.3	1.37	2.20	0.00	0.00
131	1.58	0.38	1.27	0.89	0.75	1.30	0.04	1.26	3.51	3.14	2.25	2.76	1.8	0.3	1.38	2.20	0.00	0.00
137	1.54	0.33	1.36	1.03	0.68	1.52	0.04	1.48	3.65	3.32	2.29	2.97	0.5	0.3	1.44	2.20	0.00	0.00
161	1.96	0.28	1.34	1.06	0.85	1.46	0.02	1.44	3.49	3.24	2.18	2.64	1.0	0.2	1.37	2.20	0.00	0.00
170	2.13	0.36	1.55	1.19	0.66	1.38	0.00	1.38	3.54	3.18	1.99	2.88	1.5	0.0	1.14	2.20	0.03	0.00
173	1.94	0.43	1.64	1.21	0.84	1.30	0.00	1.30	3.58	3.14	1.93	2.74	1.8	0.0	1.07	2.20	0.15	0.00
Avg.	1.88	0.43	1.52	1.09	0.85	1.38	0.02	1.36	3.62	3.18	2.10	2.77	1.4	0.1	1.25	2.20	0.03	0.00
						Semi-matte paper 3 (D_y max. = 1.57)												
19	1.99	0.46	1.54	1.08	0.63	1.27	0.00	1.27	3.60	3.21	2.13	2.97	2.3	0.0	1.18	2.90	0.11	0.00
130	1.61	0.33	1.18	0.85	0.66	1.35	0.03	1.32	3.60	3.24	2.39	2.94	2.1	0.2	1.54	2.90	0.00	0.00
132	1.61	0.29	1.23	0.94	0.85	1.47	0.02	1.45	3.76	3.31	2.37	2.91	1.1	0.1	1.47	2.90	0.00	0.00
Avg.	1.74	0.36	1.32	0.96	0.71	1.36	0.02	1.35	3.65	3.25	2.30	2.94	1.8	0.1	1.40	2.90	0.04	0.00

Within each group there is a considerable fluctuation of DS_n but the data show conclusively that the negatives of relatively high density scale yield the best prints when printed on positive material of relatively low contrast, and vice versa.

It is noteworthy that:

(a) The maximum print density is never as great as the maximum density of the positive material and in many cases is appreciably less.

TABLE XII. Characteristics of the first-choice prints. Average values for various scene groups and contrast grades.

Group No.	No. of prints	Log BS_0	D_n min.	D_n max.	DS_n	$\bar{D}_n$	D_p min.	D_p max.	DS_p	Log E_0	Log E_y max.	Log E_y min.	Log $\bar{E}_y$	$s\theta_y$	$h\theta_y$	$\bar{G}_y$	$-\Delta h$	$-\Delta s$
Experimental paper 00 (D_y max. = 1.85)																		
I	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
II	1	2.47	0.30	2.12	1.82	1.00	0.00	1.78	1.78	3.66	3.42	1.60	2.66	1.1	0.0	0.97	0.00	0.0
III	3	2.44	0.25	1.95	1.70	0.64	0.02	1.65	1.63	3.57	3.34	1.64	2.92	2.5	0.2	0.94	0.00	0.0
III-P	3	—	0.41	2.41	2.00	1.01	0.01	1.71	1.70	3.82	3.42	1.41	2.84	1.6	0.1	0.85	0.00	0.0
IV	4	2.56	0.65	2.36	1.78	1.09	0.02	1.77	1.75	4.06	3.40	1.62	2.96	1.3	0.1	0.98	0.04	0.0
V	1	2.68	0.67	2.90	2.23	1.23	0.00	1.80	1.80	4.06	3.44	1.21	2.83	0.8	0.0	0.81	0.43	0.0
V-P	1	—	0.12	1.95	1.83	0.64	0.00	1.64	1.64	3.41	3.33	1.80	2.77	2.7	0.0	0.88	0.00	0.0
Avg.	(13)	2.52	0.44	2.28	1.85	0.94	0.02	1.72	1.70	3.82	3.39	1.56	2.72	1.7	0.1	0.92	0.04	0.0
Semi-matte paper 0 (D_y max. = 1.56)																		
I	2	2.11	0.47	1.80	1.34	0.91	0.00	1.35	1.35	3.40	2.96	1.62	2.49	1.4	0.0	1.00	0.00	0.0
II	5	2.32	0.37	1.70	1.34	0.80	0.01	1.40	1.39	3.38	2.99	1.64	2.58	1.1	0.1	1.02	0.02	0.0
III	15	2.30	0.45	1.84	1.38	0.93	0.01	1.40	1.39	3.46	3.00	1.62	2.54	1.1	0.1	1.00	0.02	0.0
III-P	11	—	0.34	1.71	1.36	0.82	0.01	1.39	1.38	3.33	3.00	1.63	2.51	1.2	0.1	1.01	0.07	0.0
IV	7	2.50	0.48	1.99	1.51	0.93	0.00	1.42	1.42	3.56	3.02	1.51	2.63	1.0	0.0	0.94	0.04	0.0
V	3	2.17	0.88	2.17	1.29	1.47	0.00	1.33	1.33	3.82	2.95	1.66	2.36	1.4	0.0	1.02	0.03	0.0
V-P	2	—	0.44	1.75	1.31	0.92	0.00	1.20	1.20	3.26	2.87	1.55	2.34	1.8	0.0	0.92	0.08	0.0
Avg.	(35)	2.32	0.45	1.83	1.38	0.93	0.005	1.38	1.38	3.45	2.99	1.61	2.52	1.2	0.05	1.00	0.04	0.0
Semi-matte paper 1 (D_y max. = 1.56)																		
I	12	2.07	0.49	1.73	1.24	1.06	0.01	1.44	1.43	3.61	3.10	1.87	2.55	1.1	0.1	1.15	0.01	0.0
II	20	2.21	0.43	1.67	1.24	1.00	0.02	1.46	1.44	3.56	3.12	1.88	2.62	1.0	0.1	1.16	0.02	0.0
III	12	2.42	0.41	1.76	1.35	0.89	0.01	1.46	1.45	3.54	3.12	1.78	2.64	0.9	0.1	1.08	0.05	0.0
III-P	16	—	0.49	1.79	1.30	0.98	0.01	1.45	1.44	3.56	3.12	1.81	2.58	1.0	0.1	1.12	0.08	0.0
IV	5	2.57	0.61	2.10	1.49	1.06	0.00	1.46	1.46	3.78	3.13	1.64	2.72	1.0	0.0	0.98	0.13	0.0
V	7	2.22	0.57	1.86	1.30	1.02	0.01	1.40	1.39	3.64	3.08	1.79	2.61	1.2	0.1	1.09	0.03	0.0
V-P	3	—	0.43	1.70	1.27	0.88	0.01	1.38	1.37	3.46	3.08	1.81	2.57	1.1	0.1	1.08	0.03	0.0
Avg.	(75)	2.26	0.47	1.77	1.29	0.99	0.01	1.44	1.43	3.58	3.11	1.82	2.60	1.0	0.1	1.13	0.05	0.0
Semi-Matte paper 2 (D_y max. = 1.58)																		
I	10	1.83	0.48	1.58	1.10	0.97	0.01	1.36	1.35	3.66	3.18	2.08	2.69	1.5	0.1	1.22	0.04	0.0
II	10	1.88	0.43	1.52	1.09	0.85	0.02	1.38	1.36	3.62	3.18	2.10	2.77	1.4	0.1	1.25	0.02	0.0
III	6	1.92	0.39	1.44	1.04	0.72	0.02	1.36	1.34	3.59	3.19	2.13	2.87	1.5	0.2	1.26	0.01	0.0
III-P	5	—	0.44	1.55	1.11	0.88	0.01	1.39	1.38	3.62	3.20	2.10	2.74	1.3	0.1	1.21	0.00	0.0
IV	3	2.56	0.35	1.57	1.23	0.65	0.00	1.36	1.36	3.50	3.17	1.94	2.85	1.6	0.0	1.11	0.13	0.0
V	10	2.18	0.56	1.78	1.22	0.97	0.02	1.36	1.34	3.76	3.20	1.98	2.79	1.4	0.1	1.13	0.16	0.0
V-P	3	—	0.44	1.52	1.09	0.83	0.07	1.39	1.32	3.70	3.19	1.77	2.87	1.5	0.3	1.27	0.10	0.0
Avg.	(47)	2.00	0.46	1.58	1.13	0.87	0.02	1.38	1.36	3.65	3.18	2.04	2.57	1.4	0.15	1.22	0.06	0.0
Semi-matte paper 3 (D_y max. = 1.57)																		
I	4	1.55	0.35	1.19	0.85	0.78	0.04	1.40	1.35	3.64	3.28	2.42	2.86	1.8	0.3	1.57	0.00	0.0
II	3	1.74	0.36	1.32	0.96	0.71	0.02	1.36	1.35	3.65	3.25	3.20	2.94	2.1	0.1	1.40	0.04	0.0
III	1	2.12	0.41	1.52	1.11	0.66	0.005	1.50	1.50	3.71	3.35	2.24	3.05	0.6	0.0	1.34	0.00	0.0
III-P	1	—	0.16	1.02	0.86	0.42	0.06	1.50	1.44	3.49	3.35	2.49	3.07	0.8	0.4	1.64	0.00	0.0
IV	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
V	1	2.28	0.11	1.19	1.08	0.45	0.00	1.13	1.13	3.25	3.16	2.08	2.80	2.9	0.0	1.05	0.16	0.0
V-P	2	—	0.12	0.85	0.73	0.35	0.11	1.06	0.95	3.24	3.15	2.41	2.89	2.9	0.5	1.47	0.08	0.0
Avg.	(12)	1.82	0.28	1.18	0.90	0.63	0.04	1.33	1.29	3.54	3.25	2.36	2.92	2.0	0.2	1.46	0.04	0.0
Semi-matte paper 4 (D_y max. = 1.56)																		
V-P	4	—	0.12	0.66	0.54	0.26	0.02	1.29	1.27	3.45	3.32	2.78	3.19	3.2	0.2	2.37	0.00	0.0

(b) The minimum print density is in no case greater than 0.07 and frequently is 0.0.

(c) Log E_y max. tends (for any contrast grade) to be constant.

(d) $s\theta_y$ tends to be high, increasing generally with the contrast grade.

(e) $h\theta_y$ tends to be low, in some cases 0.0.

(f) $-\Delta s$ never exceeds 0.0.

(g) $-\Delta h$ is in some cases appreciably greater than 0, although on the average its value is low.

Further reference will be made to Table XI in the discussion of special problems to be taken up later.

B. Criteria of Printing Exposure

If it is desired to place print-making on a firm scientific foundation, it is necessary that the criterion of correct printing exposure shall be a *unique* characteristic of the negative. Obviously this characteristic must also be *measurable.* Among criteria that have been suggested from time to time may be mentioned "the maximum density in which detail is desired," "the maximum significant density," "the face density," "the density of the deepest shadow in which detail is desired," etc. None of these is unique since different observers may disagree radically in choosing the negative density represented by these descriptive phrases. The whole system would be thrown into the realm of guesswork and personal opinion if the printing criteria were expressed in such indefinite and ambiguous terms. We therefor reject all such criteria as not fulfilling the requirement of *uniqueness.*

There are, however, at least three negative characteristics which meet the requirements of uniqueness and of measurability. They are:

(a) Maximum negative density, D_n max.
(b) Minimum negative density, D_n min.
(c) Average negative density $\bar{D}_n$.

One of the purposes of classifying the scenes into groups having homogeneous characteristics was to answer the question: is the criterion of correct printing exposure dependent upon the characteristics of the scene? We shall now examine the data in an attempt to answer this question.

In Table XII have been assembled the average values taken from all the tabulations (typified by Table XI) relating to the first-choice prints made upon the semi-matte paper and, in addition, averages relating to those made upon the lowest contrast grade (00) of glossy material. Of particular interest are the values of the maximum, minimum, and average exposure incident upon the positive materials during printing. Thus, in column log E_y max. are the average values, for the various scene groups, of the exposure incident on the positive material corresponding to the extreme shadow of the scene, D_n min. of the negative. In the case of the 00 contrast grade, these values vary from 3.33 to 3.44, but without any systematic trend within the groups. In the case of the No. 0 contrast grade, the values vary from 2.87 to 3.02, but again without any systematic trend. For the other contrast grades, there is some fluctuation from group to group of the value of log E_y max. but in no case is a systematic trend relative to the scene type perceptible nor are the small variations which occur within each contrast-grade grouping duplicated or even similar to those which occur in others. There seems to be no reason, therefore, to suspect that the scene type has any appreciable influence upon the printing exposure corresponding to minimum negative density.

An examination of the values in column log E_y min., which refer to the printing exposure on the positive material under the maximum negative density, leads to the same conclusion. Throughout the table the fluctuations in log E_y min. are considerably greater than the fluctuations in the log E_y max. values, but no systematic relationship between these values and the scene type can be found.

Values of log $\bar{E}_y$, the average printing exposure, show more variation than those of log E_y max. However, they again confirm the conclusion that the scene type has no systematic influence on printing exposure.

Quite apart, therefore, from the question of which of these three criteria is the best from the standpoint of correct printing exposure, we feel confident that the scene type has no observable influence on the reliability of any one of them. In particular, a comparison of Groups III and III-P, representing the non-portrait and portrait types, is of interest. In the 00 section of the table we find values of 3.34 and 3.42 for log E_y max., while in the No. 0 section the two values are 3.00. For the No. 1 grade, the values are 3.12 and 3.12, while the No. 2 grade for these groups gives 3.19 and 3.20, respectively. In the case of the No. 3 contrast grade, the values are identical, even though this is a very unfavorable case because

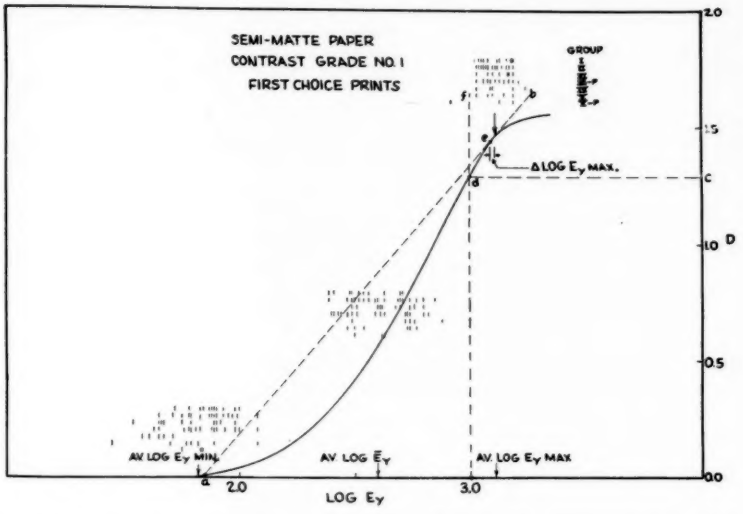

FIG. 16. Information relative to the first-choice prints made on the contrast grade No. 1. Graphic method.

only one scene is classified into each of the two groups.

In considering these data, attention should be paid to the number of prints on which the averages are based. Those averages derived from large numbers of prints obviously are more reliable than those obtained from only a small number. Hence, when trends or non-trends are indicated by the averages based on many prints, non-conformity to these trends based on small numbers should be strongly discounted.

From careful study of the data in Table XII we conclude that the criterion of correct printing exposure is not a function of scene type (as defined by our system of classification), or, if it is related in some way to scene type, the present study, either because of experimental errors or lack of a sufficient number of cases, has failed to reveal the dependency. Attention is also directed to the following relationships:

(a) The average value of object brightness scale, log BS_0, decreases as the "contrast" of the positive material increases.

(b) The average value of the negative density scale DS_n also decreases in the same order.

(c) The maximum print density tends to be appreciably lower than the available maximum density of the positive material and this difference seems to increase as the "contrast" of the positive material increases.

(d) The minimum print densities are on the average low, being only slightly greater than 0.0.

(e) The limiting gradient in the shadow region tends to be high, while the limiting gradient in the highlight region is low.

(f) Values of $-\Delta h$ and $-\Delta s$ confirm previous conclusions, namely, that no part of the negative tonal scale in the shadow region is discarded in making the print, while it is frequently found that a portion of the negative tonal scale in the highlight region is not used in making the print.

In Fig. 16 the information relative to the first-choice prints made on the contrast grade No. 1 is shown. The short vertical lines just above the shoulder of the characteristic curve were located as follows: The D_p max. for a given print is located at c on the density scale at the right as shown. A horizontal line intersects the characteristic curve at d. A perpendicular dropped from this point to the log E_y scale gives the value of log E_y max. for that print. A vertical line through the point d establishes the position of the short vertical line f. In a similar manner short vertical lines were established for all of the first-choice prints on this material. These are grouped in rows displaced vertically, these rows corresponding to

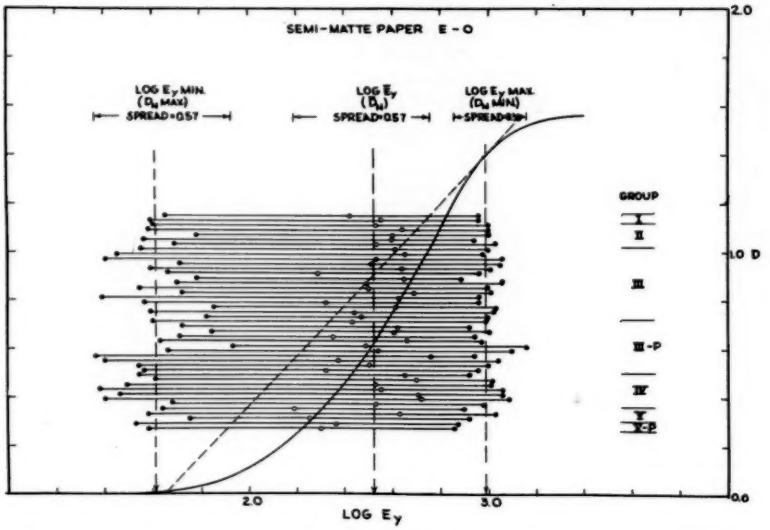

FIG. 17. Portion of the characteristic curve of the positive material used for making each of the first-choice prints on the No. 0 contrast grade.

the scene-type classification, Group I at the top, II just below, etc. The fact that these horizontal spacings for the various scene-type groups almost completely overlap each other is further verification of the conclusion already drawn that scene type has no systematic influence upon the correct printing exposure.

The small arrow just above the characteristic curve is located at the *average* value of log E_y max.

The groups of short vertical lines just above the extreme toe of the characteristic curve represent the distribution of the log E_y min. values for this group of prints, these being determined as set forth in the discussion of Fig. 15. The groups of short vertical lines near the middle portion of the characteristic curve were established by using the values of $\bar{D}_n$. The distribution of these index marks in the horizontal direction with respect to group indicates again that scene type shows no systematic correlation with these possible printing criteria.

Correlations Based on Log $E_0 = D_n + b$

An inspection of Fig. 16 shows that values of log E_y max. tend to group themselves quite closely about the average value indicated by the small arrow. In fact, the total spread from this average is only $+0.23$ and -0.18. There are 66 members in this group and if four (only 6 percent) of these are discarded, the spread is reduced to ± 0.11. This suggests that correctly exposed prints are obtained when the exposure incident upon the positive material under the lowest density of the negative is kept relatively constant. Such a condition is realized if the correct printing exposure E_0 is defined by the relationship

$$\log E_0 = D_n \text{ min.} + b, \tag{1}$$

where b is a constant associated with the sensitivity or speed of the positive material. The value of b is given by the average value of log E_y max. for the group.

We may likewise express the correct printing exposure in terms of the other two possible criteria being considered, namely, the maximum negative density and the average negative density. Thus:

$$\log E_0 = D_n \text{ max.} + \text{average log } E_y \text{ min.}; \tag{2}$$

$$\log E_0 = \bar{D}_n + \text{average log } \bar{E}_y. \tag{3}$$

The use of these very simple relationships of course assumes a direct linear proportionality between the criterion being considered and the correct printing exposure, and we must not lose sight of the fact that possibly some other per-

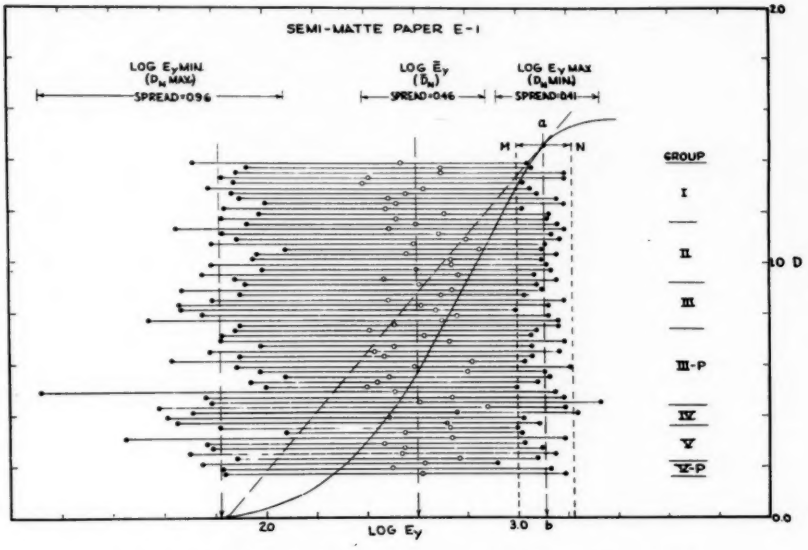

FIG. 18. Location of the first-choice prints on the No. 1 contrast grade.

fectly definite but less simple relationship may exist between these criteria and correct printing exposure. However, since it is desirable from the standpoint of practical applications to establish the simplest possible relationship between a measurable characteristic of the negative and the correct printing exposure, we shall first of all examine the consequences of assuming the existence of the simple relationship indicated by the expressions (1), (2), and (3).

The graphic method of presenting these data, as shown in Fig. 16, serves satisfactorily to illustrate the range over which the three printing criteria spread and to emphasize the absence of dependence of any one of the criteria on scene type. As plotted in Fig. 16 there is no connection between the maximum and minimum density points for a particular print, but for some purposes it is necessary to know what portion of the characteristic curve of the positive material is used for making each of these first-choice prints. To show this the data for the No. 0 contrast grade are shown in Fig. 17. In this case each horizontal line represents a first-choice print. The extremity to the right when projected on the D-log E curve indicates the D_p max., and when dropped to the log E_y axis gives log E_y max. The extremity of the line to the left gives D_p min. and log E_y min. The small circle on this line is established by use of the measured $\bar{D}_n$ and therefore when projected to the log E_y axis gives log $\bar{E}_p$.

These horizontal lines are grouped from top to bottom according to the scene classification, as shown at the right, and it can be seen that there is no trend either to the right or to the left as we pass through various scene types. In Figs. 18 and 19 similar graphic representation for the data of contrast grades No. 1 and No. 2 (semi-matte) is shown.

In Fig. 20 are shown the data from the first-choice prints made on the special experimental glossy-surface paper (contrast grade 00) having a very long exposure scale. It is significant that even with this material of very unusual curve shape the D_p max. values are closely clustered in the "shoulder" region. The data for all other groups, including the glossy and matte surfaces, exhibit the same general characteristics as are shown in Figs. 17 to 20, inclusive.

A careful analysis of the data in Table XII and in Figs. 17, 18, and 19, leads to the conclusion that the reliability of any one of the three printing criteria being considered is not dependent upon the scene type. For the present purpose, therefore, it is no longer necessary to segregate the statistical data with respect to

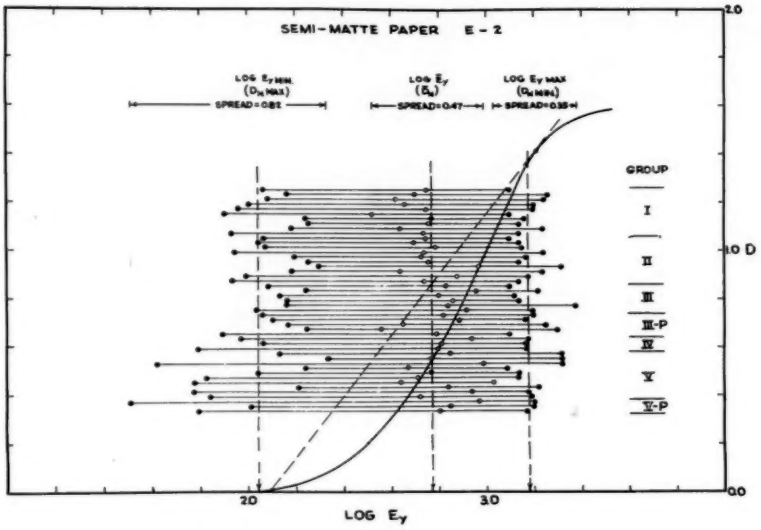

FIG. 19. Location of the first-choice prints on the No. 2 contrast grade.

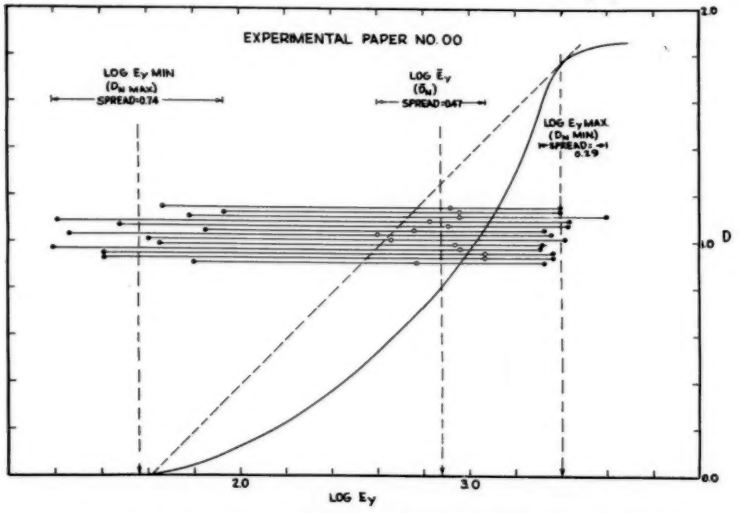

FIG. 20. Location of the first-choice prints on the No. 00 contrast grade.

scene type. Hence it is permissible to average all of the data relating to a given positive material as characterized by contrast grade and surface characteristics. We may condense this mass of data to a brief form, as shown in Table XIII. These are the averages for each of the positive materials shown in Table XII and the averages for the groups of prints made on glossy and matte surface papers. The values of average negative density scale DS_n are interesting since they show the way in which this value decreases as the contrast of the positive material increases.

The values of the limiting gradient at the shadow end of the used part of the positive material $s\theta_y$ are also worthy of note. They tend to be quite high and to increase systematically

TABLE XIII. Characteristics of first-choice prints. Averages for each contrast grade and surface.

Paper surface	Contrast grade	No. of prints	Log BS_0	D_n min.	D_n max.	DS_n	$\bar{D}_n$	D_p min.	D_p max.	DS_p	Log E_0	Log E_y max.	Log E_y min.	Log $\bar{E}_y$	$s\theta_y$	$h\theta_y$	$\bar{G}_y$	$-\Delta h$	$-\Delta s$
Glossy	00	13	2.52	0.44	2.28	1.85	0.94	0.02	1.72	1.70	3.82	3.39	1.56	2.88	1.7	0.10	0.92	0.04	0.00
Semi-matte	0	35	2.32	0.45	1.83	1.38	0.93	0.005	1.38	1.38	3.45	2.99	1.61	2.52	1.2	0.05	1.00	0.04	0.00
Semi-matte	1	75	2.26	0.47	1.77	1.29	0.99	0.01	1.44	1.43	3.58	3.11	1.82	2.60	1.0	0.10	1.13	0.05	0.00
Semi-matte	2	47	2.00	0.46	1.58	1.13	0.87	0.02	1.38	1.36	3.65	3.18	2.04	2.77	1.4	0.15	1.22	0.06	0.00
Semi-matte	3	12	1.82	0.28	1.18	0.90	0.63	0.04	1.33	1.29	3.54	3.25	2.36	2.92	2.0	0.20	1.46	0.04	0.00
Semi-matte	4	4		0.12	0.66	0.54	0.26	0.02	1.29	1.27	3.45	3.32	2.78	3.19	3.2	0.20	2.37	0.00	0.00
Glossy	0	7	2.40	0.44	1.84	1.40	0.99	0.00	1.46	1.46	3.50	2.98	1.59	2.51	1.3	0.02	1.05	0.12	0.00
Glossy	1	8	2.14	0.42	1.71	1.29	0.90	0.00	1.53	1.53	3.50	3.04	1.75	2.54	1.5	0.01	1.18	0.07	0.00
Glossy	2	6	2.21	0.33	1.55	1.22	0.73	0.00	1.51	1.51	3.45	3.12	1.90	2.71	1.8	0.04	1.25	0.10	0.00
Matte	1	5	2.37	0.45	1.89	1.44	0.93	0.00	1.14	1.14	3.84	3.40	1.96	2.91	0.7	0.00	0.79	0.09	0.00
Matte	2	16	2.25	0.39	1.65	1.26	0.83	0.00	1.21	1.21	3.85	3.50	2.24	3.02	0.8	0.03	0.96	0.06	0.00

TABLE XIV. Spread values of log E_y max., log E_y min., and log $\bar{E}_y$ for the relationship log $E_y = \bar{D}_n + b$.

Contrast grade	Surface	log E_y max. Average	log E_y max. Spread	log E_y min. Average	log E_y min. Spread	log $\bar{E}_y$ Average	log $\bar{E}_y$ Spread
00	glossy	3.39	0.29	1.56	0.74	2.88	0.47
0	semi-matte	2.99	.30	1.61	.57	2.52	.57
1	semi-matte	3.11	.41	1.82	.96	2.60	.49
2	semi-matte	3.18	.35	2.04	.82	2.77	.47
3	semi-matte	3.25	.23	2.36	.66	2.92	.31
4	semi-matte	3.32	.07	2.78	.30	3.19	.05
0	glossy	2.98	.12	1.59	.46	2.51	.32
1	glossy	3.04	.24	1.75	.48	2.54	.38
2	glossy	3.12	.11	1.90	.36	2.71	.25
1	matte	3.40	.34	1.96	.47	2.91	.46
2	matte	3.50	.20	2.24	.53	3.02	.34
Average			.24		.58		.37

as the contrast of the positive material is increased. It appears that these high values of gradient at this end of the tonal scale are necessary in order that the relatively low gradients of the negative will produce satisfactory rendering of shadow detail in the reproduction. The values of gradient at the other end, that is the highlight end, of the used part of the positive material $h\theta_y$ are rather low but, again, tend to show a slight increase as the contrast of the positive material increases. In printing, these gradient values combine with the relatively high gradients in the same part of the negative tonal scale to give acceptable detail rendering in the highlight region. It must be realized, of course, that these remarks apply to statistical averages. A high percentage of individual cases exists in which the gradient at the highlight end of the positive material is actually zero, meaning that there is no reproduction of detail in many prints in the extreme highlight region of the tonal scale.

In the upper portion of each of Figs. 17, 18, 19, and 20 the log E spread in the values of the three printing criteria is shown. It will be seen that the spread for the minimum negative density is the least in all cases.

For convenience of comparison the spread values for all groups of prints are shown in Table XIV, along with the corresponding values of log E_y max., log E_y min., and log $\bar{E}_y$. It will be noted that the average spread for the log E_y max. values is appreciably lower than for the other two possible criteria.

An inspection of all of the plotted data (in a form similar to that shown in Figs. 17 to 20, inclusive) shows that in many of the groups there are one or two values which depart widely from the average of the group. By neglecting nine of these widely scattered values out of a total of 186 (approximately 5 percent), the average spread in the value of log E_y max. is reduced to 0.2.

There is some question as to the best possible mode of treating data of this kind in order to evaluate the relative merit of the various possible criteria of correct printing exposure. For many purposes departures from a functional relationship are usually expressed in terms of the average deviation from the mean. It is doubtful whether this method is most significant for this particular problem. The total spread is probably of greater significance because if a large number of negatives are to be printed according to some measured negative characteristic, it is more important to know the number of cases in which a high quality print will not be obtained than to evaluate the average deviation from the best possible printing exposure. Hence we shall, for the time being at least, assume that the total spread is the best index of the merit of a printing

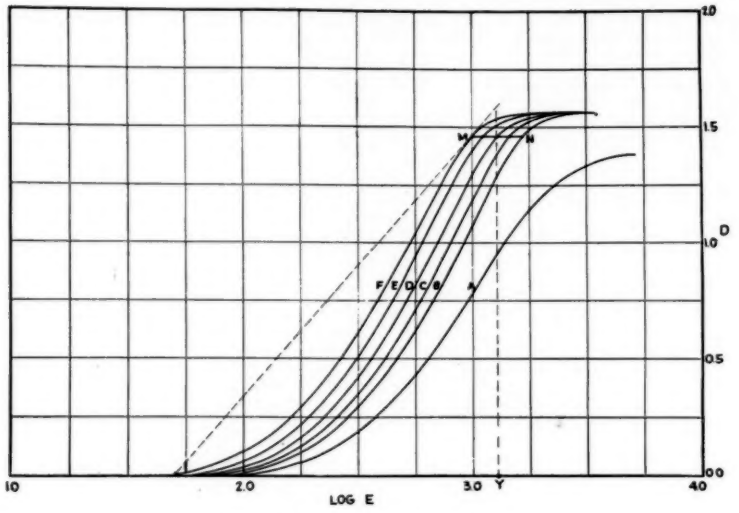

FIG. 21. Development amplitude.

criterion. On this assumption we must conclude from the evidence at hand that, of the three possible criteria being considered, the minimum negative density is appreciably superior to either the maximum negative density or to the average negative density, at least when the simple relationship between the negative characteristic and the correct printing exposure as defined by the relationship

$$\log E_0 = D_n + b$$

is assumed.

As shown in Table V the log exposure increment used in making a series of prints from a given negative on a particular contrast grade of paper varied from 0.12 to 0.04, depending upon the contrast of the positive material. It is evident, therefore, from a consideration of the data in Table XIV that the spread in the log E_y max. values is sufficient to give a print which is one or more steps lighter or darker than the most correctly exposed print. This statement is based on the assumption that all prints are subjected to a fixed extent of development. Obviously it is desirable in a scientific system of making prints to use a fixed temperature and fixed agitation and fixed time of development. No criterion for computing printing exposure has been found thus far which makes this possible if the best possible print is to be obtained. However, by abandoning the fixed processing requirement, excellent results can be obtained. This is illustrated by Fig. 21, the curves of which are for the same positive material as that shown in Fig. 18.

It is well known that for practically all developing-out papers, particularly of the chloride and chlorobromide types, prolongation of the development time beyond a relatively short value produces no change in the curve *shape*, but does cause a translation of the curve to the left (direction of less exposure). Curve *A* is that obtained with a development time of 15 seconds. It will be noted that the maximum density is appreciably below the other curves of the set and that equilibrium curve shape has not yet been obtained because of the short development time. Curve *B* is that obtained in 30 seconds, the least development time giving the equilibrium curve *shape*, and curve *F* is that resulting from a development for 160 seconds, the greatest time which can be used without danger of the production of objectionable fog. It is evident that increasing the development time is equivalent to increasing the *effective printing speed* of the positive material. The magnitude of the available speed change is given by the length of the line *MN*. It is appropriate to call this *development amplitude* which, in this case, is

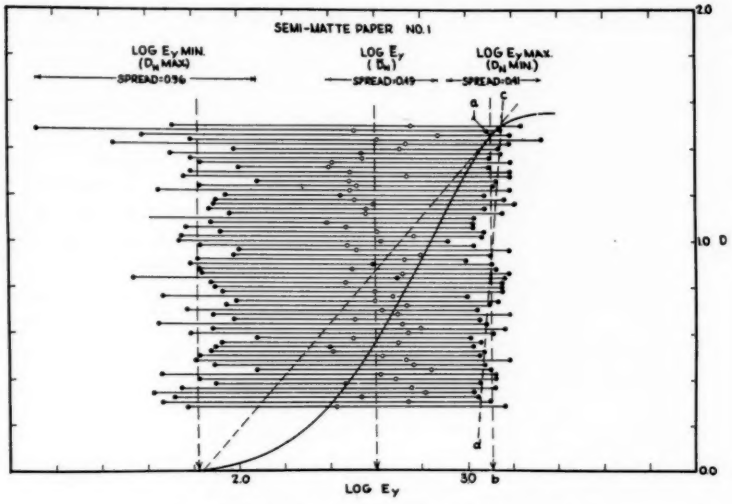

FIG. 22. First-choice prints arranged in order of increasing D_n min.

0.23 (in log units). Now, if a perpendicular be dropped from the midpoint of line MN to the log E_y axis, point Y, the value of log E_y thus determined becomes the *mid* (or median) *effective printing speed* of the material. The corresponding development time may appropriately be called the *mid development time.*

The development amplitude depends but little, if any, on the contrast grade and, in fact, is fairly constant for various kinds of chloride and chlorobromide developing-out papers, its value in general lying between 0.25 and 0.35.

Returning now to Fig. 18, let us assume that the characteristic curve there shown is that corresponding to the mid development time; the *mid speed* is found to be 3.11 (in log units). A horizontal line MN is drawn equivalent in length to the line MN in Fig. 21 with its midpoint at log $E_y = 3.11$. Perpendicular dotted lines dropped from M and N are found to embrace all of the right-hand extremities of the print lines except two. Thus, by computing the printing time from the formula log $E_0 = D_n$ min. $+3.11$, and developing the prints by inspection for times varying from 30 to 160 seconds, prints of first-choice quality will be obtained from 97 percent of the negatives printed, provided the operator is sufficiently expert to judge when the print should be removed from the developer.

Correlations Based on Log $E_0 = a \cdot D_n + b'$

As mentioned previously, it should not be assumed *a priori* that the correct printing exposure log E_0 is related to a possible printing criterion by a simple one-to-one proportionality. Inspection of the data reveals a tendency for the value of log E_0 to increase at a somewhat greater rate, with respect to D_n min., than that demanded by the simplest rule. This may be seen in Fig. 22 where the data from Fig. 18 have been replotted. Here the horizontal lines which refer to the individual first-choice prints have been arranged so that the one made from the negative having the lowest value of minimum density is at the bottom and the value of D_n min. increases progressively upward. The extremities of these lines at the right now show a tendency to move, on the average, to the right from the bottom to the top of the figure, that is with increasing values of D_n min. This means that first-choice prints made from negatives of low D_n min. tend to have lower maximum densities than those made from negatives of high minimum density. A straight line *cd* drawn through the average position of the right-hand extremities of these print lines is not perpendicular to the log E axis, thus indicating that a one-to-one proportionality does not best represent the rela-

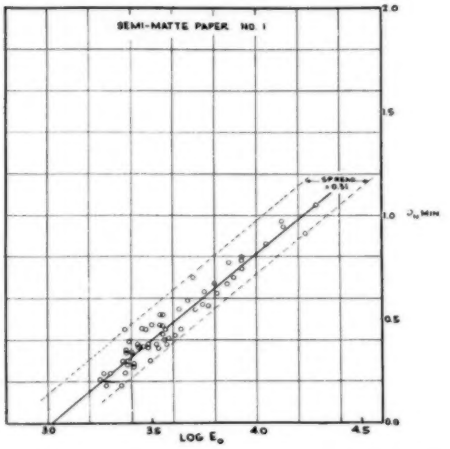

FIG. 23. D_n min. *vs.* log E_0 for first-choice prints on No. 1 contrast grade.

tionship between log E_0 and D_n min. for this group of first-choice prints.

It will be noted that in many cases where the first-choice prints have relatively low maximum densities the density scale of the negative is so great that the highlight area is reproduced in the print by zero density and in many cases an appreciable portion of the negative tonal scale in the highlight region has been pushed off the characteristic curve of the positive material at the toe end. It does not seem reasonable to assume that these prints of relatively low D max. are chosen for the sake of the low D max. In explanation of this situation we can only say that all of the high quality (first-choice) prints exhibit a fair degree of detail reproduction in the extreme shadow region. This does not mean that reproduction of shadow detail is a necessary and sufficient condition for excellent photographic quality. This may only be a condition that is closely correlated with other factors that are the chief determinants of print quality.

If the limiting gradient of the negative at the shadow end is low, a high print density D_p max. cannot be achieved because of the lowered gradient of the positive material when the print density is made to approach the maximum density of the positive material. When the limiting gradient of the negative in the shadow region is relatively high, a higher maximum print density can be achieved without undue loss of gradient or detail discrimination in the reproduction. Unfortunately there is no direct relationship between the minimum negative density and the corresponding gradient. If there were no flare light in the camera (or if the flare factor were constant) such a relationship would exist and could be deduced directly from the sensitometric curve of the material. However, from the evidence it appears that on the average a low negative minimum density is associated with a low limiting gradient, and vice versa. It is therefore a *gradient* requirement, in relation to print quality, which makes it necessary to be satisfied with low maximum print densities in some cases. Certainly it does not seem possible to account for this condition by saying that such prints are chosen as of best possible quality simply because the D max. is low, but rather that a low D max. must be accepted in order to get satisfactory tonal rendering.

In Fig. 23 values of D_n min. have been plotted against the corresponding values of correct printing exposure, log E_0, for the first-choice prints made on the No. 1 contrast grade positive material, semi-matte surface. The straight line as drawn through these plotted points was established by the method of least squares and as a measure of the correlation existing between these variables, the Bravais-Pearson coefficient was computed in the usual manner. In Fig. 24 the same graphic representation is shown for

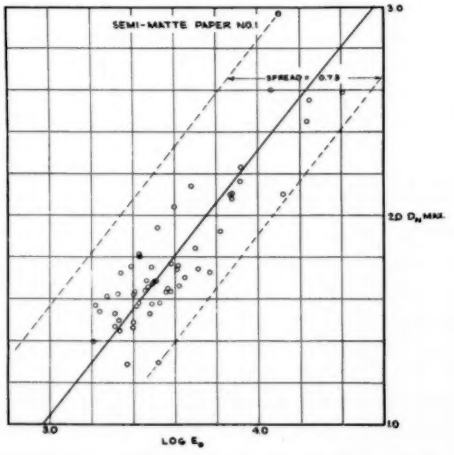

FIG. 24. D_n max. *vs.* log E_0 for first-choice prints on No. 1 contrast grade.

D_n max. for the same group of first-choice prints, and in Fig. 25, the relationship between $\bar{D}_n$ and log E_0.

Inspection of Figs. 23 to 25, inclusive, indicates that these relationships are represented quite satisfactorily by straight lines. In Fig. 25 there is some indication that a curved line might give a better fit with the experimentally determined points. The curvature of such a line, however, would be very slight and hence we have chosen in all cases to regard the straight line as a satisfactory representation of the experimental data. These relationships may therefore be represented by the equation of a straight line in the usual form,

$$x=\frac{1}{a}\cdot y+b',$$

in which x in all cases represents log E_0 and y, the various aspects of negative density.

Inspection of Fig. 23 shows that the points cluster closely around the straight line which has a slope of 0.81. The total spread, 0.31, is given by the horizontal distance between the dotted lines parallel to the solid line drawn so as to embrace all the points. This spread is somewhat less than that shown in Table XIV for the same data, using the simpler relationship,

$$\log E_0 = D_n \text{ min.} + b.$$

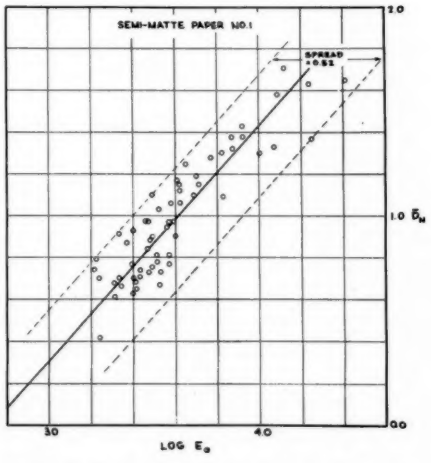

FIG. 25. $\bar{D}_n$ *vs.* log E_0 for first-choice prints on No. 1 contrast grade.

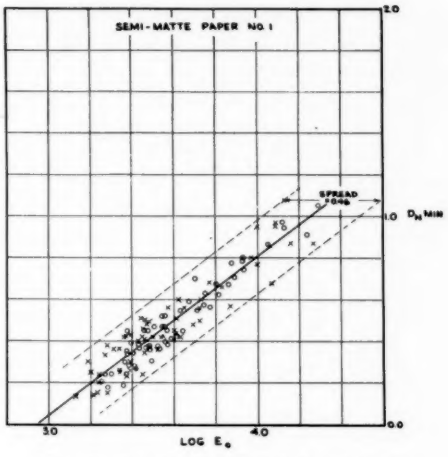

FIG. 26. Result of adding printing data for second-choice prints.

Figure 24 indicates that the use of D_n max. as a printing criterion still gives very poor correlation as compared with the value of D_n min., the total spread being 0.73 as compared with 0.96, using the simpler relationship. In Fig. 25 the slope of the straight line is 1.16 and the total spread is 0.52. This spread is almost exactly the same as that obtained for the same data by using the simpler relationship. The correlation coefficients corresponding to the curves in these figures are: 0.95, 0.87, and 0.84. The evidence indicates strongly that the relation between each of the possible printing criteria and the logarithm of the correct printing exposure is a linear one and is somewhat better represented by a straight line having a slope other than unity.

It will be remembered that complete data are also available on the second-choice prints made from each negative, the second choice being with respect to the most suitable contrast grade of positive material. In all cases the second-choice, as well as the first-choice prints, received the best possible printing exposure for the contrast grade of positive material used. These additional data relative to correct printing exposure are of considerable value, particularly in view of the conclusions which must be drawn when we consider a criterion for choosing the correct contrast grade on which to print a given negative of known density characteristics. As will be seen

in a subsequent section, no criterion for choosing the best contrast grade has been found which will discriminate uniquely between two adjacent contrast grades. Hence, if the best criterion available be used, in about half the cases the contrast grade will be off by one step. It seems justifiable, therefore, to average in with the printing information from the first-choice prints all of the printing information relative to second-choice prints. It is probable that the average from the two sets of data will be fully as reliable, if not more reliable, as an indication of the best possible printing exposure, when it is considered that in many cases the contrast grade, given by the best available criterion, will be one grade lower or higher than the best possible grade. It should be emphasized again that although we speak of second-choice prints they are not second-choice with respect to the best possible printing exposure, but with respect to the contrast grade.

The consequences of adding the printing data relative to the second-choice prints are shown in Fig. 26, which is a duplicate of Fig. 23, to which have been added the crosses, these representing the printing exposures for the second-choice prints made on this material. The solid line is that determined by the method of least squares by using all of the observations and has a slope of 0.76, which is only slightly different from that applying to the first-choice prints alone. The total spread is indicated by the dotted line and is increased somewhat, from 0.31 to 0.46.

The data for all of the positive materials used in this work were plotted as shown in Fig. 26. The correlation coefficients and the constants in the equation of the most probable straight line representing the data were computed. The results are shown in Table XV. The first column indicates the contrast grade, the second, the surface, and the third, the number of prints used in establishing the correlation. The fourth and fifth columns indicate the factors involved, and in column Q are the values of the correlation coefficient for each relationship. In columns a and b' are the constants of the straight line. It will be seen that only the first five groups of prints have been used in obtaining the average values. The groups of prints made on the glossy and matte surface materials contain so few members that the statistical averages are less certain than those for the groups containing many more prints.

TABLE XV. Correlation coefficients.

Paper	Surface	No. of prints			Q	a	b'
00	glossy	12	D_n min.	log E_0	0.96	0.86	3.29
			$\bar{D}_n$	log E_0	.91	.94	2.79
			D_n max.	log E_0	.77	.98	1.46
0	semi-matte	82	D_n min.	log E_0	.91	.79	2.89
			$\bar{D}_n$	log E_0	.89	1.14	2.67
			D_n max.	log E_0	.78	1.48	2.21
1	semi-matte	127	D_n min.	log E_0	.94	.75	2.94
			$\bar{D}_n$	log E_0	.89	1.12	2.73
			D_n max.	log E_0	.86	1.28	2.19
2	semi-matte	86	D_n min.	log E_0	.93	.70	3.02
			$\bar{D}_n$	log E_0	.91	1.13	2.87
			D_n max.	log E_0	.84	1.29	2.40
3	semi-matte	32	D_n min.	log E_0	.87	.71	3.14
			$\bar{D}_n$	log E_0	.92	1.23	3.05
			D_n max.	log E_0	.76	1.74	2.89
Average			D_n min.	log E_0	.92	.75	
			$\bar{D}_n$	log E_0	.90	1.13	
			D_n max.	log E_0	.82	1.36	
0	glossy	7	D_n min.	log E_0	.98	.72	2.89
1	glossy	8	D_n min.	log E_0	.98	.75	2.89
2	glossy	6	D_n min.	log E_0	.86	.74	3.00
1	matte	5	D_n min.	log E_0	.99	.64	3.08
2	matte	16	D_n min.	log E_0	.92	.84	3.28

The correlation coefficients for the D_n min. relationship are somewhat higher than for either of the other two printing criteria being considered. The correlation coefficients for $\bar{D}_n$ are, however, only a little lower than for D_n min. The correlation coefficients for the D_n max. relationships are markedly lower than for the other two. We therefore feel justified in concluding that the maximum negative density is a very poor criterion of correct printing exposure and, in fact, the correlation is so decidedly inferior to that obtained with the other criteria that we shall reject it as useless.

On the basis of the correlation coefficient values it would be difficult to discriminate between the usefulness of the D_n min. and the $\bar{D}_n$ criteria. However, on the basis of total spread, the minimum negative density seems to be appreciably superior to the average negative density.

It should be remembered that all of the negatives used in this work, with the exception of five,* were normally exposed and developed

* The exceptions are shown in the following table. The last two columns designate the way in which these depart from our previous definition of normalcy.

Negative No.	Group	Exposure	Development
20X	III-P	under	under
21X	III-P	normal	under
22X	III-P	under	normal
24X	V-P	under	under
25X	V-P	normal	under

according to the definition at the beginning of Section V. In previous communications from these Laboratories[2] evidence has been submitted showing that the average negative density is, in fact, a very satisfactory criterion of correct printing exposure. The groups of negatives used in this previous work contained many instances of definite underexposure and it is quite likely that under such conditions the average negative density may be a more satisfactory criterion than the minimum negative density. In underexposed negatives the minimum density is zero and hence becomes a poor, if not useless, criterion of correct printing exposure. For a group of negatives containing many such cases it is possible and even probable that the average negative density may very well be found to be *on the average* a better guide to correct printing exposure than the minimum negative density. This communication, however, deals with normally exposed negatives and the evidence is quite conclusive that under these conditions the minimum negative density is the most reliable criterion of correct printing exposure.

Turning again to Table XV, it will be seen that the values of a for the D_n min. relationship vary from 0.70 to 0.86, the average being 0.75. The average for the five small groups at the bottom of the table is 0.74. There seems to be no correlation between these slope values and the contrast grade or surface, but, from the standpoint of tone reproduction theory, it seems almost certain that this slope value will depend upon the shape of the shoulder of the positive characteristic. In dealing with a group of positive materials having similar curve shapes, there seems to be no reason to use as a value for a anything other than the average for the group which, in this case, is 0.75. The evidence indicates definitely that the best correlation is obtained by using the expression $\log E_0 = a \cdot D_n + b'$. However, the spread values as illustrated in Figs. 23 to 26, inclusive, are so great that even this relationship will not give prints of best quality if the processing conditions are constant. Development by inspection must be resorted to in order to obtain a high percentage of first-quality prints. This being the case, there seems to be little reason to use the relationship mentioned above rather than the simpler one, $\log E_0 = D_n + b$. It seems safe to conclude that this simpler relation should give very excellent results for most practical purposes. There may be special problems of course where the use of the more complicated relationship would be warranted.

C. Criterion for Selection of Contrast Grade

When a print is to be made from a negative, the operator must make two decisions: (1) the contrast grade of positive material to be used, and (2) the printing exposure. Usually the selection of the positive material is made first, the choice being determined by the skill of the operator in estimating the quality of the negative and by his knowledge of the characteristics of the available printing materials. Having decided upon the positive material he then estimates the required exposure and makes a trial print. In this discussion these two subjects are treated in the reverse order. This procedure is necessary because we must rely upon data derived from the correctly exposed prints to establish correlation between some unique and measurable characteristic of the negative and the contrast grade of positive material which produces the best possible positive.

In discussing this subject it is frequently said that a print of satisfactory quality can be obtained only when the exposure scale of the positive material, $\log ES_p$, is approximately equivalent in value to the density scale of the negative DS_n. That these two quantities must bear some relation to each other is apparent from a consideration of the conventional tone reproduction diagram shown in Fig. 27. This shows that the density scale of the negative, which in the case illustrated extends from the point a_n to c_n on the negative curve in the second quadrant, becomes the modulator of the exposure to which the positive material is subjected during printing, resulting in densities on the positive material extending from c_p to a_p. If the density scale of the negative is greater than the exposure scale of the positive material, as illustrated by negative No. Z in Fig. 14, all of the density differences which are in the negative will not be reproduced in the positive, sacrifice of such detail reproduction being necessary either in the highlight or shadow region, or in both. On the

other hand, if the density scale of the negative is less than the exposure scale of the positive material, and if the highest light is represented by a low positive density, a low D max. will be obtained in the print. If the printing exposure is increased to give a high D max. in the print, the minimum density will probably be unduly high. From these general statements it seems reasonable to seek some relationship between DS_n and log ES_y as a guide for the selection of the contrast grade of positive material which will result in a print of maximum quality.

Thus far we have used the term *exposure scale* in a general sense and we must now define it more precisely. It is evident that a positive material has the capacity to reproduce exposure differences from the point at which its gradient becomes slightly greater than zero to the point where, with increasing exposure, this gradient again becomes zero. These two points may be considered to limit the *total available* exposure scale of the positive material. Experience has shown, however, that all of this exposure scale is not *useful* for making prints from negatives having the usual gradient characteristics.

The problem of defining the *useful* or *effective* exposure scale of a positive material was discussed at some length in a previous communication from these Laboratories.[6] For the type of negatives used in that work and for the particular scene which served as the test object, it was concluded that the maximum useful exposure scale of a positive material lies between the two points on the characteristic curve where the gradient is 0.2. It must be remembered that the negatives used in that work were very fully exposed and utilized only the straight-line portion of the negative material characteristic. (This does not mean that the D_n-log B_0 relationship was entirely linear.) Moreover, only one scene* was used and,

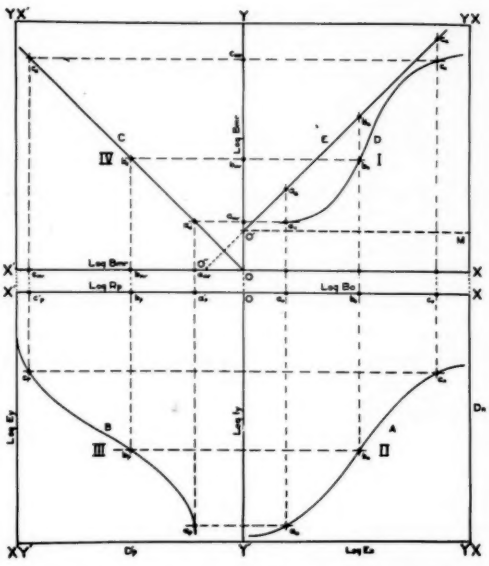

FIG. 27. Conventional tone reproduction diagram.

as was stated at the time, the conclusions as to the gradient limits of the total useful exposure scale of the negative material should not be assumed to apply for a wide range of negative characteristics and scene types. In fact, in the last section of the communication it was concluded that these limits could not be expected to be valid for scenes differing widely with respect to brightness scale BS_0. Even with the limited range of variables studied at that time it was found that the gradient values at the points limiting the useful exposure scale of the positive material used varied from 0.16 for positive materials of relatively low contrast to 1.20 for positive materials of high contrast.

Nevertheless, for lack of a better method, it has been our custom during recent years to evaluate the total useful exposure scale of a developing-out paper in terms of the 0.2-limiting gradient points. This is illustrated in Fig. 2 where the points b' and a' designate the 0.2 gradient points. The values of log exposure scale, log E_y, shown in Table IV were determined by this method.

The present work has made available a great amount of additional information bearing directly on this subject and it is evident from these new data that the 0.2-gradient method is quite

[6] L. A. Jones, "The contrast of photographic printing paper," J. Frank. Inst. **202**, 177 (1926); **203**, 111 (1927); **204**, 41 (1927).

* This scene was chosen as typical, resembling in many characteristics the majority of pictures that are taken by amateurs. It may be described as a front-lighted, sunlit scene of a semi-distant landscape type containing a wide variety of objects, architectural as well as natural. The brightness scale, approximately 56, is somewhat below the average for exterior scenes. Visible detail is distributed rather uniformly from shadow to highlight and interest is not concentrated predominantly in any particular part of the tonal scale.

inadequate for determining the useful exposure scale of developing-out papers when a great diversity of negative characteristics is involved. These diversities result from variations in the following factors: (a) the brightness scale values of the scenes photographed, (b) the curve shape of negative materials used, (c) the extent of development used in making the negative, (d) the amount of flare light present in the camera, and (e) the exposure to which the negative material is subjected. The data shown graphically in Figs. 17, 18, and 19, and numerically in Tables XII and XIII support the statement relative to the inadequacy of the 0.2-gradient method of determining the magnitude of the useful exposure scale of a positive material. Thus it will be seen by reference to Table XII that the average maximum density D_p max. for the first-choice prints made on the No. 0 grade of semi-matte paper is 1.38 and the gradient $s\theta_y$ corresponding to this density is 1.2. Likewise, for the No. 1 grade of paper the average D_p max. is 1.44 and the corresponding gradient 1.0, while for the No. 2 contrast group D_p max. is 1.38 and the corresponding limiting gradient 1.4.

An inspection of the values in each of the sections of Table XII shows no definite systematic dependence of $s\theta_y$ upon the type of scene. While these values are not the same for all groups, the variation appears to be random and its pattern is not repeated in the several sections relating to the positive materials of different contrast grade. Hence we feel justified in averaging the data from all different scene type groups to obtain the most probable values of $s\theta_y$ and, consequently, of D_p min. for each of the positive material contrast grades. These final averages are shown in Table XIII. Considering the contrast grades of the same surface characteristics, it will be seen that there is a definite tendency for the value of $s\theta_y$ to increase with the contrast of the positive material. This is clearly evident and quite definite for the five groups made on semi-matte paper (shown in the first section of Table XIII). It is also apparent in the three groups made on glossy paper and the two groups made on matte paper. Unfortunately only a relatively small number of negatives were printed on the glossy and matte surfaces and hence the averages resulting from these cannot have as great significance as those derived from the much larger number of prints made on the materials of semi-matte surface. The glossy surface, low contrast (00) experimental paper shown in the first line of the table exhibits the one exception to this rather general relationship between $s\theta_y$ and contrast grade. As pointed out previously, the curve shape of this material differs widely from that of the other materials used. In particular, its D max. is abnormally high. It is not strange, therefore, that in this respect this one material appears to be out of line with the others. A consideration of the tone reproduction aspects of this problem explains the behavior of the 00 material.

Turning now to the other end of the tonal scale, we see that the D_p min. values are all low, the averages for the groups tending to increase slightly with the increasing contrast of the positive material. The range, however, is not great, extending for the semi-matte materials from 0.005 to 0.04. It is true that the value for the No. 4 contrast grade is somewhat less than that for the No. 3. It must be remembered, however, that only four first-choice prints were made on the No. 4 contrast grade and hence this average cannot be considered to be of as great significance as those averages made from larger groups. The limiting gradients at the highlight end of the tonal scale $h\theta_y$ are also low, the averages being of the order of 0.1 and, again, there is a definite tendency for these values to increase with the contrast of the positive material.

We must therefore modify radically our present method for finding the magnitude and the location on the characteristic curve of the *useful exposure scale* of the positive material for the reproduction of normally exposed, normally developed negatives of a wide variety of scene types. An inspection of Figs. 17 to 20, inclusive, shows that the magnitude of the useful exposure scale varies over a considerable range when individual negatives are considered. The particular value we wish to establish now is the statistical average as derived from the use of a large number of negatives, all of which yield prints of first-choice quality on the positive material in question. It seems reasonable to adopt this statistical average as most meaning-

ful for the purpose of specifying this characteristic of a positive material.

Tone reproduction theory indicates definitely that the useful exposure scale of a photographic material is limited only by its failure to reproduce brightness differences satisfactorily and hence the limits of such usefulness must be sought in terms of gradient characteristics.

The horizontal lines terminated by small black dots, in Fig. 18, represent the first-choice prints which were made on this positive material, No. 1 contrast, semi-matte surface. The length of each line is given by

$$\log E_y \text{ max.} - \log E_y \text{ min.} = \log ES_p = D_n \text{ max.} - D_n \text{ min.} = DS_n.$$

The average value of DS_n for this group of negatives is 1.29 and hence *on the average* the *useful* or *effective* exposure scale of this material is also 1.29. This value is derived entirely from the judgment data and hence is a psychophysically determined datum. It is not dependent on any assumptions based upon tone reproduction theory nor is its value determined by sensitometric procedures involving measurement of either the shapes or positions of the characteristic curves of the negative and positive materials concerned.

Prints from all of these negatives (Fig. 18) were also made on the No. 0 and No. 2 contrast grades. The group of judges agreed that all such prints were either of second- or third-choice quality. The question may well be asked why some of the negatives represented by the lines which extend well to the left in Fig. 18 did not yield better prints by the use of a positive material having a greater exposure scale; or why, in the case of those lines which terminate at the left well above the toe of the characteristic curve, were not better results obtained by use of a positive material having a shorter exposure scale. We shall not attempt to answer these questions at present except to say that the consensus of opinion of the group of judges was definitely that these prints made on a No. 1 grade were superior in quality to those made on a material having either a greater or lesser exposure scale.

Now if we wish a single value to associate with this positive material (No. 1 contrast grade) to represent the most probable value of DS_n which will yield first-quality prints, we can only use the average DS_n for this group of negatives, namely, 1.29. It is true that first-choice prints were obtained on this positive material with negatives having values of a density scale other than 1.29. In fact, these values spread over a total range of from 1.02 to 1.54. However, the probability of obtaining a first-choice print by using any value of DS_n (within this range) other than 1.29 is less than when a value of 1.29 is used.

The statistically determined values which define the characteristics of the *average positive* for each of the print groups available may now be tabulated as shown in Table XVI. The values of log ES_y given in the last column are obtained by subtracting the average log E_y min. from the average log E_y max. These are equal to the average DS_n in each case. We shall define the exposure scale determined in this way as the *useful exposure scale.*

The useful exposure scales for the semi-matte materials and the extra low contrast experimental

TABLE XVI. Average characteristics of first-choice positives.

Paper Surface	Contrast	Number of prints	Log E_y min.	Log E_y max.	D_p max.	D_p min.	DS_p	$\bar{G}_y$	$h\vartheta_y$	$s\theta_y$	Log ES_y
Glossy	00	13	1.56	3.39	1.72	0.02	1.70	0.92	0.1	1.7	1.85
Semi-matte	0	35	1.61	2.99	1.38	0.005	1.38	1.00	0.05	1.2	1.38
Semi-matte	1	75	1.82	3.11	1.44	0.01	1.43	1.13	0.10	1.0	1.29
Semi-matte	2	47	2.04	3.18	1.38	0.02	1.36	1.22	0.15	1.4	1.13
Semi-matte	3	12	2.36	3.25	1.33	0.04	1.29	1.46	0.20	2.0	0.90
Semi-matte	4	4	2.78	3.32	1.29	0.02	1.27	2.37	0.20	3.2	0.54
Glossy	0	7	1.59	2.98	1.46	0.00	1.46	1.05	0.00	1.3	1.40
Glossy	1	8	1.75	3.04	1.53	0.00	1.53	1.18	0.00	1.5	1.29
Glossy	2	6	1.90	3.12	1.51	0.00	1.51	1.25	0.00	1.8	1.22
Matte	1	5	1.96	3.40	1.14	0.00	1.14	0.79	0.00	0.7	1.44
Matte	2	16	2.24	3.50	1.21	0.00	1.21	0.96	0.10	0.8	1.26

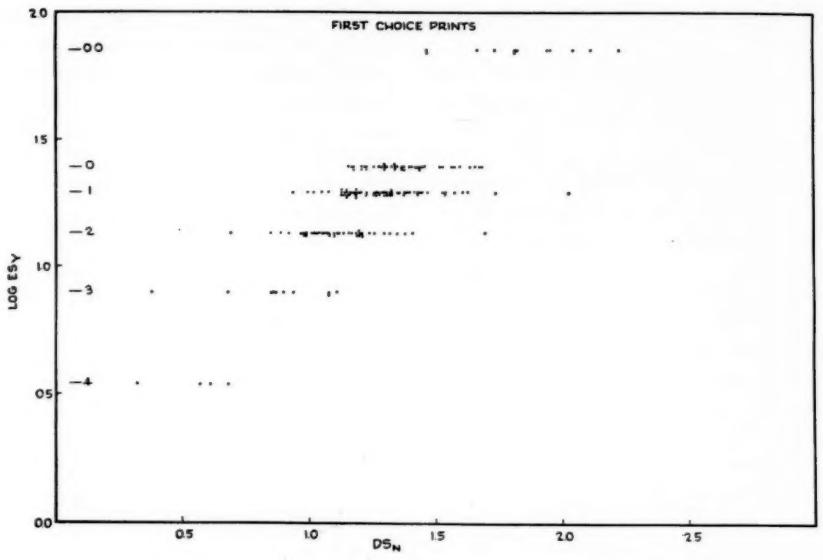

FIG. 28. Experimental data relating paper log exposure scale and negative density scale.

glossy material extend from 0.54 (No. 4) to 1.85 (No. 00). First-choice prints were obtained from all negatives ranging in density scale from 0.32 to 2.23 on these six contrast grades. No first-choice prints were made on the No. 5 grade which is a little more contrasty than No. 4. No material of less contrast than the No. 00 was available so we cannot say with certainty that some negatives would not have yielded a better print on such a material. However, only 13 out of 200 negatives required the No. 00 paper and it seems unlikely that a softer paper was needed.

In making prints we wish to measure the density scale of the negative and from this determine the proper contrast grade of positive material. In the majority of cases the measured values of DS_n will not be equal to any one of the exposure scale values of the available papers. Suppose the DS_n is found to be 1.20. This lies between the log ES_p of 1.29 for No. 1 paper and 1.14 for No. 2 paper, but is closer to 1.14. Should the negative, therefore, be printed on No. 2 paper? The first impulse is to assume that it should and that the shift from one paper to the next should occur at a point exactly half way between them. The evidence presented so far, however, does not give us any assurance that this method will yield the best results. It is necessary to examine the data in another form to arrive at any conclusive answer to this question.

As a beginning it is helpful to study the data in Fig. 28. Here the DS_n for each negative is plotted with respect to the useful log exposure scale of the paper on which a first-choice print was obtained. The graph is of great interest because it shows clearly that the correlation between negative density scale and paper exposure scale for best quality prints is not a high one. There is a wide scatter in the points, resulting in considerable overlap for the various papers. In other words, negative density scale is not a perfect criterion for choosing the paper contrast grade. Its use will lead to first-choice prints in the majority of cases but in many individual cases it will also lead to second-choice prints, and in a few instances to third-choice prints. This, of course, is a disappointing conclusion. In this respect it differs markedly from the conclusion regarding the best exposure criterion. D_n min. was found to give high correlation with optimum printing exposure and was found to be distinctly superior to $\bar{D}_n$ and very

much better than D_n max. It has been suggested that DS_n will fail in many cases as a criterion for choosing paper contrast grade for the same reason that D_n max. fails as an exposure criterion. It is probably true that if DS_n were a perfect criterion for choosing paper contrast grade then D_n max. would necessarily be almost as successful as D_n min. as an exposure criterion. This relationship between the exposure criterion and the criterion for the choice of contrast grade is of interest but it does not lead to any useful solution of the problem.

It might be felt at this point that the situation is hopeless and that the negative density scale criterion for choosing the paper contrast grade should be abandoned. However, no other unique and measurable negative characteristic has been discovered which is useful as a substitute criterion. Moreover, further analysis of the results obtained with a DS_n criterion has led us to the belief that the situation is not nearly as bad as it appears on the surface. In the first place, second-choice prints are in practically all cases high quality prints. This is especially true for prints made from negatives which lie in the region of transition from one paper grade to another. For these border line cases (and for the overlap cases found in Fig. 28) the second-choice prints are often essentially *equal* to first-choice prints in quality and are actually *interchangeable* with first-choice prints without appreciable loss in quality. Occasionally even third-choice prints are interchangeable with the first-choice prints without serious loss in quality. These facts are revealed by a closer examination of the original judgment data, a sample of which is shown in Table XVII. Here we have, for a number of negatives, the *score* (as obtained by the method described in Section IV-F) received by each contrast grade from the group of judges. The contrast grade having the highest score is recorded in the column designated as "first choice." The contrast grade having the next highest score is rated as "second choice," etc. Now it can be seen that these scores are often close. This occurs because a contrast grade falling in second place was actually rated in first place by a number of judges, though not by the majority. Similarly, a contrast grade falling in third place was actually rated in first place by some judges, in second place by others, and in third place by the majority. It is significant that many judges exclaimed over the difficulty of deciding which of the three contrast grades was the best. In Table XVII we note, for example, that for negative No. 162 the score is 62 for No. 2 paper, 62 for No. 1 paper, and 56 for No. 0 paper. Here No. 2 and No. 1 contrast grades are perfectly interchangeable for first place and No. 0 has such a high score that it could arbitrarily be given first place without offending more than a few judges. For negative No. 158 the score is 68 for No. 1 paper, 61 for No. 2 paper, and 51 for No. 0 paper. Again the score is close and the quality obtained from the three grades of paper must vary but little.

TABLE XVII. Sample of original judgment data.

Scene No.	First choice		Second choice		Third choice	
	Contrast grade	Score	Contrast grade	Score	Contrast grade	Score
8X	1	74	2	56	0	50
12	2	72	1	58	3	50
14	1	71	2	71	3	38
15	2	72	1	63	0	45
16X	1	71	2	56	0	52
29	1	64	0	58	2	54
29X	00	87	0	57	1	36
34X	1	71	2	62	3	47
59	1	67	2	64	0	50
60	1	70	2	58	0	42
65	3	68	2	65	1	47
66	3	83	2	55	1	42
106	2	76	3	54	1	50
114	1	70	2	56	0	52
120	2	78	1	58	3	42
108	3	85	2	54	4	41
117	2	73	3	55	1	52
122	2	78	3	57	1	46
129	2	70	1	64	0	46
142	1	71	2	70	0	40
150	1	76	2	64	0	40
152	3	71	2	70	1	39
158	1	68	2	61	0	51
162	2	62	1	62	0	56
168	1	71	2	62	0	47
175	1	68	0	57	2	55
176	1	73	2	63	0	44

On the other hand, for negative No. 29X the score is 87 for No. 00 paper, 57 for No. 0 paper, and 36 for No. 1 paper. Here there is a fairly strong preference for the No. 00 paper and we would probably lose considerable quality by arbitrarily insisting on the use of No. 0 or No. 1 papers. But in this case the density scale of the negative is 1.82 and there is no need to call for any contrast grade other than No. 00. In the former examples, the density scale was 1.15 for

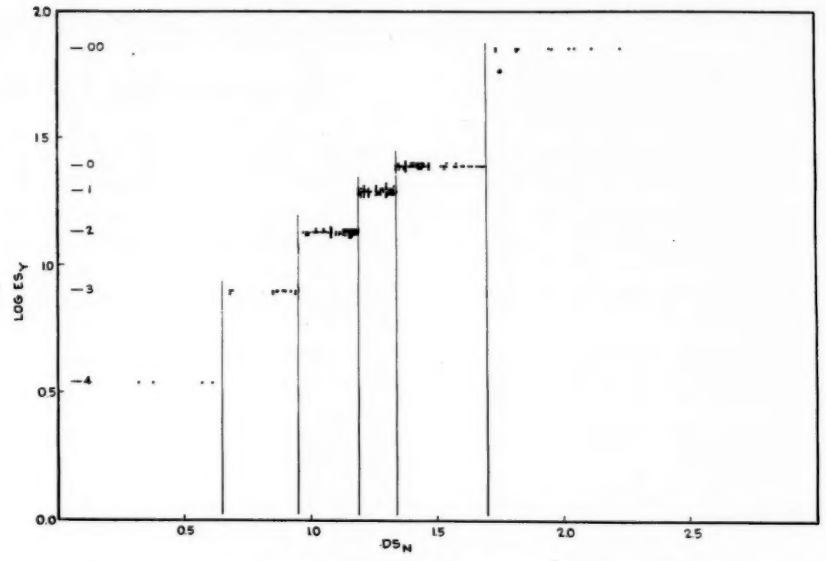

FIG. 29. Data from Fig. 28 replotted in such a manner that no overlap occurs.

both negatives and inspection of Fig. 28 shows that this falls in the region where overlap occurs and where arbitrary exchanging of contrast grades may be necessary if a workable and unambiguous system is to be achieved.

It, therefore, is possible to replot the data in Fig. 28 in such a manner that no overlap occurs and still retain a high level of print quality. This has been done in Fig. 29. The principle employed was that of making the lowest possible number of shifts in paper contrast grade and of balancing the number of shifts made in the direction of higher contrast by an approximately equal number made in the direction of lower contrast. In other words, an ambiguous relationship was converted to an unambiguous one with the least possible distortion in the original judgment data. By this means we achieve a relationship which can be put to practical use. The graph in Fig. 29 now tells us what contrast grade of paper to use in printing any negative for which the density scale DS_n is known. Of course, this relationship is as yet established only for these *particular* papers. However, it can serve as a model from which a generalized relation may be drawn. It is, of course, important that a method be derived which will apply to any set of photographic papers regardless of their particular spacing on the log ES_p scale.

The procedure followed in obtaining a relationship between DS_n and log ES_p may seem forced and artificial. This we grant, and it must be borne in mind that the print quality obtained by its use will not be the highest possible quality. But what other course is there to follow? Either we must make the best of a somewhat imperfect relationship or face the prospect of having no criterion whatever for choosing the paper contrast grade.

It is of great interest to note that the transition from one paper to the next in Fig. 29 does not always occur at a density scale value which is numerically half way between the useful log ES_p values for the two papers. For example, a negative having a density scale of 1.68 would be printed on No. 0 paper, which has a log exposure scale of 1.35, rather than on No. 00 paper, which has a log exposure scale of 1.83. In other words, it appears that for long-scale negatives which lie between two papers, it is usually better to let the density scale exceed the log exposure scale of the paper rather than fall short of it. To ignore this principle and choose the half-way point between two papers as the transition point is to sacrifice print quality unnecessarily.

For short-scale negatives it appears that the transition point between two papers should lie closer to the harder of the two papers. This means that a negative having a density scale of 0.66 would be printed on No. 3 paper which has a log exposure scale of 0.90 rather than on No. 4 paper which has a scale of 0.54. In other words, for short-scale negatives, which fall between these two papers, it is often desirable to choose the contrast grade which will cause the density scale of the negative to be less than the log exposure scale of the paper.

For papers of normal contrast grade and for negatives having density scales in the neighborhood of 1.2, the transition point does seem to lie approximately half way between the two log exposure scale values.

A somewhat striking method of summarizing the relation between DS_n and log ES_p is shown in Fig. 30. Here we have the log ES_p for each of the papers plotted as points on the upper horizontal scale. The lower horizontal scale represents the DS_n for the negatives which are to be printed on these particular papers. Thus all the negatives having density scales lying between 1.29 and 1.70 are to be printed on No. 0 paper having a log exposure scale of 1.35. The base of each shaded triangle embraces the negatives which should be printed on the paper found at the apex of the

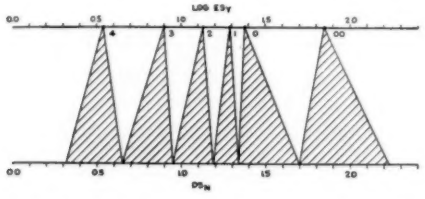

FIG. 30. Method of summarizing the relation between negative density scale and paper log exposure scale.

triangle. It can be readily seen that these triangles are not all isosceles and that they lean toward the center of the diagram. This is a graphic representation of the fact that for contrasty negatives the density scale of the negative tends to exceed the log exposure scale of the paper and for flat negatives the density scale of the negative tends to be less than the log exposure scale of the paper. The practical application of this diagram in the making of photographic prints by sensitometric control will be discussed in a later section of this report.

VI. SENSITOMETRIC METHODS

A purely psychophysical method based on the judgment of print quality was used in the previous section (V) to establish statistical average values for the characteristics of the developing-out papers used in this work. Where a large number of samples must be tested, this statistical method is much too laborious and time consuming. A direct sensitometric method is desirable for such purposes as the control of product, obtaining numerical values for use in the specification of characteristics, or in the making of prints. It must yield values in agreement with those derived by the statistical method. Such a sensitometric method has been found and will now be discussed.

In Fig. 31 curve A is the D-log E characteristic of the No. 1 contrast grade, semi-matte surface, positive material (see Fig. 3). Curve B is the first derivative, $dD/d \log E = f \log E_y$ (see Fig. 4). The density and gradient scales are identical, as shown at the left of the figure. The part of the D-log E characteristic used in making each of the first-choice prints with this contrast grade of positive material is shown in Fig. 18. The point b in Fig. 31 is located on the log E_y scale where the value is 3.11, this being the average of the log E_y max. values for all of the first-choice prints made on this material as shown in Tables XIII and XVI. The vertical line ab drawn through this point cuts the characteristic curve at the point s and the first derivative at the point g. These give the average D max. and average $s\theta_y$ values for the first-choice prints. The point d is located on the log E_y scale at 1.82, this being the average value of the log E_y min. for all of the first-choice prints made on No. 1 paper. The vertical line cd is drawn through this point and establishes the points h and k which determine the average values for D_p min. and $h\theta_y$, respectively.

The dashed line from the point h to point s on the curve A gives the average slope of the characteristic curve between these two points. From the statistical point of view it is evident that the value of log E_y corresponding to the point s is the measure of the effective useful speed of this material. This is a consequence of our decision that the minimum negative density is the most re-

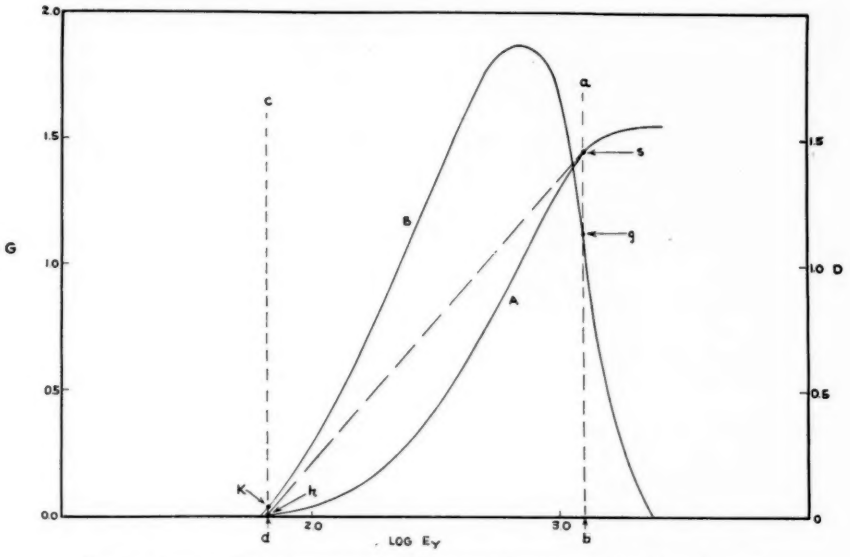

FIG. 31. Sensitometric characteristics of the useful portion of the D-log E curve.

liable criterion of the correct printing exposure. Hence we may conclude that the exposure incident on the positive material under the minimum density area of the negative is the most reasonable criterion of effective speed. As shown in Table XIV, the spread in the values of this characteristic is relatively small in all cases, these values grouping themselves closely around the average. This point also limits the useful part of the characteristic curve at the high density end and hence determines the value of the *useful limiting gradient* $h\theta_y$. It is clear then that the desired sensitometric method should locate the point s close enough to the statistically determined value to satisfy the practical requirements for specifying the characteristics of positive materials.

A. Sensitometric Method for Locating Point *s*

The coordinates of point s (Fig. 31) determine the following values: Log E_y max. and hence speed, useful maximum density, and highlight limiting gradient $s\theta_y$. If a straight line is drawn tangent to the characteristic curve A at the point s, it intersects the toe of the characteristic curve at a point very close to h. Assuming that this intersection actually occurred at the point h, it is evident that $s\theta_y$ is equal in value to the average slope of the used portion. In Table XVI in column $\bar{G}_y$ are the values of the average slope of the used portion for all of the positive materials which we have been using. And in the column $s\theta_y$ are the limiting gradients at the shadow end of the tonal scale.

It should be remembered that these are all determined by statistical judgment methods, not by sensitometry. If we confine our attention to the five contrast grades of semi-matte material on which the vast majority of the prints were made, it is seen that there is a tendency in all cases for the value of $s\theta_y$ to follow quite closely that of $\bar{G}_y$. This suggested that possibly, by selecting some point on the extreme toe of the characteristic curve and drawing a line from that point tangent to the shoulder of the characteristic curve, the point s might be located sensitometrically with sufficient precision for practical purposes. In the particular case illustrated in Fig. 31 the limiting gradient at the highlight end (point h) is 0.04. An inspection of the data for groups of first-choice prints made on other contrast grades indicates, at least in some cases, that this limiting gradient is somewhat higher.

As a first approximation, therefore, we adopted a fixed gradient of 0.10. By using the data for all of the first-choice prints and all of the contrast

TABLE XVIII. Observed and computed values of effective printing speed from first-choice prints.

Paper Surface	Contrast grade	No. of prints	From print judgments log E_y max.	From sensitometric criterion log $E_{\bar{G}=1\times\bar{G}}$	Δ
Glossy	00	13	3.39	3.40	+0.01
Semi-matte	0	35	2.99	2.98	−0.01
Semi-matte	1	75	3.11	3.11	0.00
Semi-matte	2	47	3.18	3.21	+0.03
Semi-matte	3	12	3.25	3.27	+0.02
Semi-matte	4	4	3.32	3.35	+0.03
Glossy	0	7	2.98	3.00	+0.02
Glossy	1	8	3.04	3.06	+0.02
Glossy	2	6	3.12	3.16	+0.04
Matte	1	5	3.40	3.36	−0.04
Matte	2	16	3.50	3.45	−0.05
				Average	0.02

grades and surfaces, the data shown in Table XVIII were obtained. The first two columns refer to the positive materials used. The fourth shows the data derived from the statistical print judgment. The fifth gives the value of log E_y max. obtained by the tangent line method explained in the previous paragraph. This of course is the value of log E_y where the gradient is equal to the gradient of the straight line. In the last column are the differences between the statistically and sensitometrically determined values of log E_y max. It will be seen that the departures in all cases are small and not of sufficient magnitude to be of any practical importance.

A large mass of judgment data relating to the prints of second-choice quality is also available. In many cases this print quality is almost if not entirely as good as the first choice. Even if the quality is somewhat below that of the first-choice print, the printing exposure is the best possible of that combination of negative and positive material. We therefore feel justified in using these data also for the determination of the effective speed. The results are shown in Table XIX. Here again the departures between the statistically and sensitometrically determined values of log E_y max. are small, some being positive and some negative, but none (perhaps with the exception of the No. 2 contrast matte surface) of sufficient magnitude to have any appreciable practical significance.

From this evidence we conclude that the position of the point s can be determined sensitometrically with adequate precision by locating a point on the toe of the characteristic curve where $G=0.10$ and drawing a straight line from this point tangent to the shoulder of the characteristic curve. The log E_y value at this point of tangency is a measure of the useful speed of the material, and the gradient of this point is the limiting gradient in the shadow region.

B. Sensitometric Method of Locating Point h

The coordinates of point h (Fig. 31) determine the useful minimum density and the limiting gradient in the highlight region, and hence together with the coordinates of point s determine the values of useful exposure scale, density scale, and average gradient.

The validity of using a point on the toe of the characteristic having a fixed gradient value as a means of establishing the position of point h will now be considered. An inspection of the values of $h\theta_y$ in Table XVI indicates a very definite tendency to increase as the contrast of the positive material increases. This parallels a tendency of $\bar{G}_y$ to increase also as the contrast of the positive material increases. This we consider very significant and it suggests that the limit in the highlight region is a function of the general gradient characteristics of the used portion of the curve. In other words, it appears that the gradient which limits the usefulness of the characteristic curve in the highlight region of the tonal scale is again some function of the generalized slope characteristics of the part of the characteristic curve which is used in making the print. Thus the old fractional gradient idea crops up again. Consideration of tone reproduction theory indicates that this condition is a logical one and should be expected.

It should be remembered that values of $h\theta_y$ in Tables XIII and XVI, etc., were obtained by one of two possible methods of averaging. For each first-choice print a value of $h\theta_y$ was determined corresponding to the minimum log E_y for that print and the values thus determined for the group were averaged. A goodly proportion of these individual values are zero and some of them correspond to log E_y min. values which lie well to the left of the extreme toe of the characteristic curve.

The other method of obtaining this value may be more rational from some points of view than

the one used. This consists in averaging all of the values of log E_y min. for a given group of first-choice prints and then reading, from the first derivative curve, the gradient value corresponding to this exposure value. This method results in somewhat lower limiting gradients, as is illustrated in Table XX in which the fourth column gives the values taken from Table XVI and the last shows those resulting from this second method of averaging.

Attention is again called to the fact that the values for the glossy and matte surface materials are based upon a relatively few prints. Moreover, the negatives chosen for making these prints do not represent a random cross section of the total 200 negatives used in making the prints on the semi-matte surface. It is obvious, therefore, that the averages derived for the glossy and matte surface materials are not of as great validity as those pertaining to the semi-matte materials where large numbers of prints were made on the various contrast grades. Sets of prints on the glossy surface materials from all negatives are being made and we shall soon have additional data which we confidently expect will verify those derived from the prints made on the semi-matte material.

For the purpose of deciding on a sensitometric method for locating the position of point h we shall use only the data relating to the first-choice prints made on the semi-matte positive material and the lowest contrast (00) glossy surface. In Table XX the values of $h\theta_y$ based on averages of individual limiting gradients have been multiplied by 10 and are shown in the fifth column. The values of $h\theta_y$ based upon the average log E_y min. values have been multiplied by 20 and are shown in the seventh column. In the sixth column are the values of $\bar{G}_y$ derived from the statistical source. It will be noted that there is a tendency for the values in the fifth and seventh columns to agree with those of $\bar{G}_y$. While this correlation may not be of a high order it certainly is significant of a tendency and we are convinced that the lower limit of the useful portion should be defined as a fractional part of the average slope of the used portion.

There is some uncertainty as to which of the two methods should be adopted for the determination of the average value of $h\theta_y$ from the print judgment data. The evidence presented in Table XX does not decisively favor either one of the two methods. The average of the valu shown in the fifth column is identical to that for the values in the seventh column and both agree almost perfectly with the average value of $\bar{G}_y$. However, one value of 20 $h\theta_y$ is zero and hence, according to this, the position of the point h is indeterminate. Moreover, the average of the deviation between the values in columns five and six is only 0.37, while the average of the deviations between the values in columns six and seven (even excluding the one deviation which is infinite) is 0.62. Thus the data in Table XX seem to favor somewhat the use of $0.1\bar{G}_y$ as a means of locating the point h.

Another test of the quality of the various sensitometric criteria for the locating of the point h (Fig. 31) lies in an examination of the values of exposure scale log ES_y derived as a consequence of using these criteria. In the fourth column of Table XXI are the values of log ES_y as determined by the statistical method. In the fifth column are the values of log ES_y which result from locating point h where the gradient is equal to 0.05 $\bar{G}_y$, and in the sixth column are the differences between these values and those in column four. In the seventh column are the values of log ES_y which result from placing the point h where the gradient is 0.1 $\bar{G}_y$, and in the eighth column the corresponding deviations. In the ninth column are the values of log ES_y determined by locating h at the point where the gra-

TABLE XIX. Observed and computed values of effective printing speed from second-choice prints.

Paper			From print judgments	From sensitometric criterion	
Surface	Contrast grade	No. of prints	log E_y max.	log $E_{G=1\times\bar{G}}$	Δ
Semi-matte	0	45	3.02	2.98	−0.04
Semi-matte	1	70	3.10	3.11	+0.01
Semi-matte	2	55	3.24	3.21	−0.03
Semi-matte	3	54	3.30	3.27	−0.03
Semi-matte	4	2	3.34	3.35	+0.01
Semi-matte	5	2	3.43	3.44	−0.01
Glossy	0	6	2.98	3.00	+0.02
Glossy	1	11	3.07	3.06	−0.01
Glossy	2	2	3.14	3.16	+0.02
Glossy	3	2	3.25	3.28	+0.03
Matte	1	16	3.34	3.36	+0.02
Matte	2	5	3.57	3.45	−0.12
				Average	0.03

dient has a constant value of 0.1, and in the last column the deviations resulting from this procedure.

It will be seen that the average deviation resulting from the use of a fixed gradient is greater than the average deviation resulting from the use of either of the two fractional gradient methods. The average deviation in column six is slightly less than that in column eight which apparently favors a little the use of the 0.05 $\bar{G}_y$ criterion, although this is contrary to the evidence of the data in Table XX. After carefully considering this problem from all points of view we have decided to favor the use of 0.1 $\bar{G}_y$ as a sensitometric criterion for locating the point h. Our reasons for this are as follows:

(1) Tone reproduction theory, which of course includes a consideration of the way in which the visual mechanism functions in the perception of brightness and brightness differences, indicates definitely that the gradients at the limits of the used portion of the characteristic curve of a positive material should be dependent upon the general or average gradient characteristics of the used portion. This theory is supported by the practical results of our statistical study which indicates clearly that the fixed gradient criterion does not agree as well with the statistical data as does the fractional gradient criterion.

(2) From the purely practical point of view, it seems likely that the position of the point h may be determined with somewhat greater precision by using the 0.1 $\bar{G}_y$ criterion than by using the 0.05 $\bar{G}_y$ criterion because experimentally it is less difficult to measure the higher gradient value. The use of the lower gradient value does not increase appreciably the perfection of agreement with the statistically determined values.

TABLE XX. Average values of $h\theta_y$.

Paper Surface	Contrast grade	No. of prints	From average of $h\theta_y$: $h\theta_y$	$10 \cdot h\theta_y$	$\bar{G}_y$	From average of log E_y min.: $20 \cdot h\theta_y$	$h\theta_y$
Glossy	00	13	0.10	1.0	0.92	0.00	0.00
Semi-matte	0	35	0.05	0.5	1.00	0.40	0.02
Semi-matte	1	75	0.10	1.0	1.13	0.80	0.04
Semi-matte	2	47	0.15	1.5	1.22	1.00	0.05
Semi-matte	3	12	0.20	2.0	1.46	3.00	0.15
Semi-matte	4	4	0.20	2.0	2.37	2.80	0.14
Average				1.33	1.35	1.33	

We propose, therefore, that the point h be established on the characteristic curve at the point where the gradient is 0.10 of the average gradient of the straight line drawn from that point and tangent to the shoulder of the curve. The position of this point can be determined unambiguously by the geometrical construction illustrated in Figs. 32 and 33. In Fig. 32, in which the curves A and B are identical to those in Fig. 31, a series of points a, b, c, etc., are located along the toe of the curve beginning at a point a, where the slope is just slightly greater than zero. From each of these points a straight line is drawn tangent to the shoulder of the characteristic curve A. The slope of each of these straight lines is determined. The gradient for the points a, b, c, etc., is found by erecting perpendiculars cutting the first derivative curve at a', b', c', etc. The data thus obtained are shown in Fig. 33, curve A giving the relationship between $\bar{G}_y$ and log E_y for the various points a, b, c, etc. Curve B is obtained by multiplying the gradient values for the points a, b, c, by 10 and then plotting against the corresponding log E_y values. A perpendicular dropped from the point of intersection, O, of the curves A and B (Fig. 33) is the value of log E_y at which the slope of the curve A is equal to 0.1 the slope of the tangent line, which is equal to $\bar{G}_y$.

The question may now be raised as to whether the departure from the fixed gradient value of 0.1 used in finding the values reported in Tables XVII and XIX will seriously affect the location of the point limiting the useful part of the curve in the shadow region. In Fig. 32 it is shown that the position of the limiting point, s, in the shadow region is very insensitive to the position of the limiting point in the highlight region. Thus the two tangent straight lines drawn from $G=0.02$ and $G=0.46$ change the position of the tangent point by only 0.02 in log E. This we consider of little significance, because for a wide variety of commercial materials the value of 0.10 $\bar{G}_y$ lies between 0.05 and 0.35. It must be admitted, of course, that the magnitude of this change will be determined somewhat by the shape of the curve in the shoulder region but for the vast majority of commercial developing-out papers now on the market the shoulder is seldom less sharp than the curve in Fig. 34 which we have used to illustrate this point.

TABLE XXI. Effect of various criteria on computed values of useful exposure scale.

Paper			From print judgments	From sensitometric criteria					
Surface	Contrast grade	No. of prints	Useful log ES_y	log ES_y $0.05\bar{G}$ to $1.0\bar{G}$	Δ	log ES_y $0.1\bar{G}$ to $1.0\bar{G}$	Δ	log ES_y 0.1 to $1.0\bar{G}$	Δ
00	Glossy	13	1.85	1.80	−0.05	1.78	−0.07	1.78	−0.07
0	Semi-matte	35	1.38	1.38	0.00	1.35	−0.03	1.35	−0.03
1	Semi-matte	75	1.29	1.26	−0.03	1.24	−0.05	1.24	−0.05
2	Semi-matte	47	1.13	1.13	0.00	1.11	−0.02	1.12	−0.01
3	Semi-matte	12	0.90	0.96	+0.06	0.94	+0.04	0.97	+0.07
4	Semi-matte	4	0.54	0.56	+0.02	0.54	0.00	0.59	+0.05
				Average	0.027		0.035		0.047

C. Sensitometric Method for Determining Useful Exposure Scale

The coordinates of the two points *h* and *s* (Fig. 31) determine exposure scale, density scale, and average gradient of the useful portion of the positive material characteristic curve. For practical purposes it may be desirable to choose the simpler course in locating point *h*, namely, that of using a fixed lower gradient such as 0.10. There is little difficulty in determining this gradient point with precision by carefully plotting the measured gradient values for a series of log E_y values and drawing this curve in its most probable position from the plotted points. However, the fractional gradient method can be applied with very satisfactory precision by a similar graphic technique. From the standpoint of tone reproduction theory we are convinced that it is basically sound to define the point which limits the useful portion of the characteristic curve both in the highlight and shadow regions as fractional parts of the average slope between these two points. On this basis we recommend that the useful exposure scale of a developing-out paper be defined as lying between two points, one located on the toe and the other on the shoulder of the characteristic curve. The line connecting these two points has a slope of $\bar{G}$. The gradient at the point on the toe is equal to 0.10 $\bar{G}$. The gradient at the point on the shoulder is equal to 1.0 $\bar{G}$.

D. Derivation of Characteristic Numerical Values

The evidence presented in the previous sections of this paper we feel supports strongly the proposed sensitometric method for finding the positions of two points on the characteristic curve of a positive material between which lies the useful portion of that characteristic for the purpose of making prints. It therefore becomes necessary to modify profoundly our methods of deriving numerical values which may be used as a convenient method of specifying the characteristics of these materials. The derivations of a new series of numerical values for this purpose may be illustrated by reference to Fig. 34. Curve *A* is the *D*-log *E* characteristic for a developing-out paper having a semi-matte surface. This curve was derived from density readings made on a sensitometric strip which had been subjected to standardized conditions of exposure and development. We shall not go into these detailed conditions at present except to say that the extent of development was such as to yield a curve analogous to curve *D* in Fig. 21. This development, described qualitatively on page 595, is designated as mid development. Curve *B* is the usual first derivative of curve *A*. The points *S* and *H* are located according to the technique discussed in the previous section.

The first characteristic to be considered is that of speed. As indicated previously, the effective printing speed of a positive material is determined by the exposure corresponding to the point *S*. Speed, of course, is inversely proportional to this value. It is customary to express exposure in terms of metercandle-seconds and if the reciprocals of the exposure values are determined for the commercially available current materials, numbers of inconvenient magnitude are obtained. It is desirable, therefore, to apply

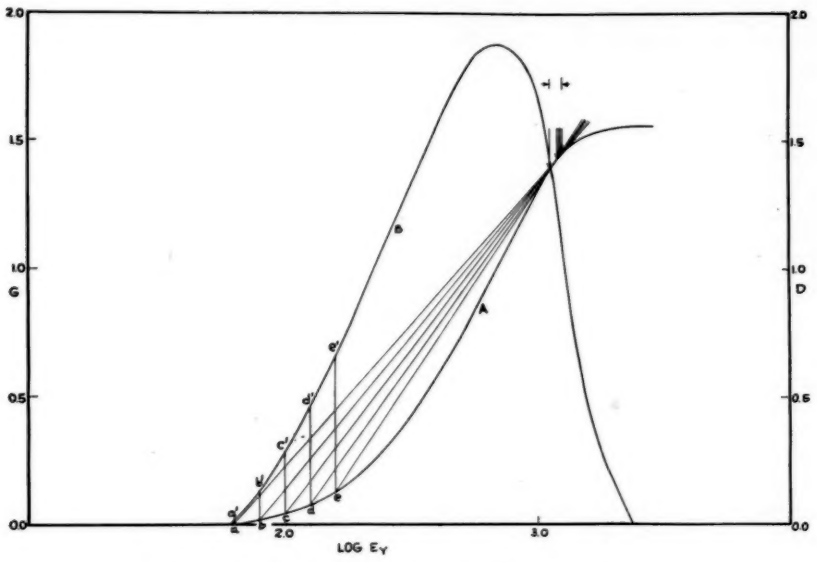

FIG. 32. Graphical method of locating the limiting gradients: $h\theta_y = 0.1\ \bar{G}_y$ and $s\theta_y = 1.0\ \bar{G}_y$.

some constant of arbitrary magnitude so that a series of numbers convenient for practical use will be obtained. We may therefore express speed formally by the equation

$$\text{Speed } (S) = k/E_{ys}.$$

If k is made equal to 10^4 the numerical values of speed for the entire range of photographic papers now generally used lie between 1.0 and 60,000.

The remaining numerical values which we consider to be adequate for the specification of the useful characteristics of photographic papers may be expressed simply and directly in terms of the coordinates of the two points S and H and the corresponding gradient values as read from the first derivative curve. We may therefore summarize these numerical values in the following table:

Speed $(S) = 10^4/E_{ys}$,
Log exposure scale $(\log ES_y) = \log E_{ys} - \log E_{yh}$,
Density scale $(DS_y) = D_{ys} - D_{yh}$,
Available maximum density $= D_y$ max.,
Useful maximum density $(D'_y \text{ max.}) = D_{ys}$,
Maximum gradient $= G_y$ max.,
Average gradient $(\bar{G}_y) = DS_y/\log ES_y$,
Limiting gradient at shadow end $(s\theta_y) = \bar{G}_y$,
Limiting gradient at highlight end $(h\theta_y) = 0.10\ \bar{G}_y$.

The numbers which express the characteristics of developing-out papers, derived from the new proposed sensitometric method, are quite different in some respects from those obtained by the method used heretofore. Some of the changes which follow the adoption of the new technique are illustrated in Table XXII. The values shown apply to the positive materials which were used in making the prints employed in our statistical

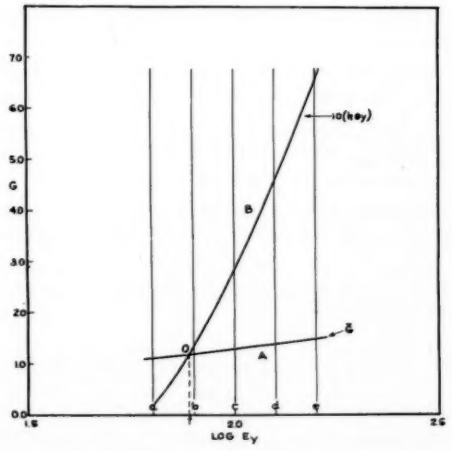

FIG. 33. Method of finding log E_y for $h\theta_y = 0.1\ \bar{G}_y$.

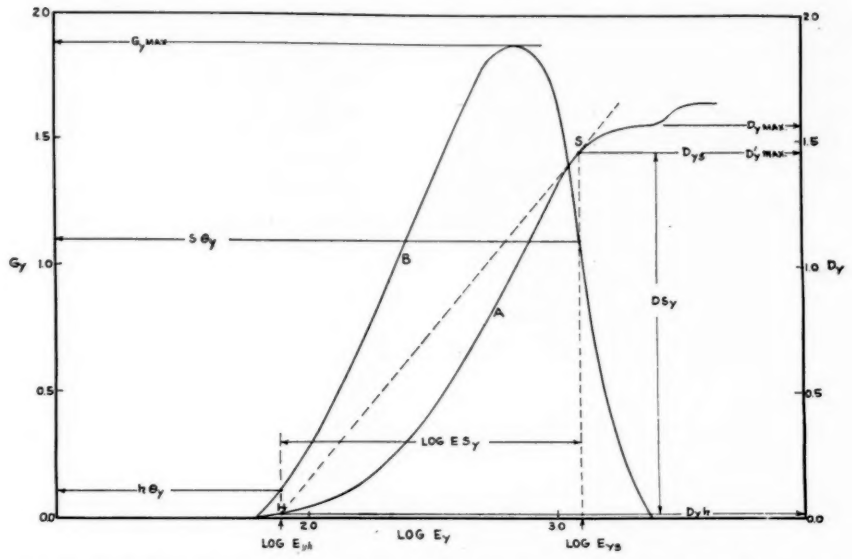

FIG. 34. Derivation of new series of numerical values for expressing the sensitometric characteristics of photographic papers.

study. In the two columns designated as Useful D max., Old and New, it will be seen that the new technique leads in all cases to appreciably lower values. The differences ΔD show that on the average the useful D max. is about 0.15 less than the available D max. The fact that D max. values for the first-choice prints are not, on the average, nearer to the available D max. of the positive materials was somewhat of a surprise to us and, in fact, the validity of the conclusion has been questioned. It has been contended that this phenomenon is not found in good quality photographic prints as furnished by the average commercial finishing establishment. The critics intimate that the conditions under which the prints used in this statistical investigation were made are very different from those existing in commercial photofinishing and that the results of these methods and techniques cannot be expected to agree with the results obtained in field practice.

To test this point a group of 98 new negatives was selected. These were made on several negative materials and represented a wide variety of scene types and the range of processing conditions usually met with in amateur finishing work. These negatives were delivered to a commercial photofinisher with instructions to make the best possible print on any one of four contrast grades of a glossy developing-out paper, the sensitometric characteristics of which had been previously determined. When these prints were delivered, values of maximum and minimum print density were measured. A summary of the results is given in Table XXIII. As indicated in the second column of the table, 35 of these negatives yielded best prints on the No. 0 grade, 33 on the No. 2 grade, 25 on the No. 3 grade, and only 3 on the No. 4 grade. In all cases the available D max. was 1.71, as indicated in the third column of the table. The maximum, minimum, and average D max. values for each group of these prints are shown in the specified columns and in the last column of the table, ΔD, are the differences between the average useful D max. and the available D max. It will be seen that these are of almost exactly the same magnitude as the values of ΔD shown in Table XXII. There are a few prints in which the maximum density is or is almost equal to the available D max. There are in each group, however, several prints in which the useful D max. is very much lower than the available D max. We feel that this evidence derived from prints made under commercial photofinishing conditions, in addition to those used in

this investigation, is conclusive proof that on the average first-choice prints show D max. values appreciably below the available D max. of the material.

Considering Table XXII, it will be seen that the new technique yields values of exposure scale somewhat lower than those based on the fixed 0.2-gradient criterion. The difference is not very great in the case of the papers of low contrast. This difference increases systematically, especially when expressed on a percentage basis, as the contrast of the positive material increases. For instance, the No. 4 grade, which on the old basis had a log ES_y value of 0.73, now shows a useful log exposure scale of only 0.54, a decrease of approximately 30 percent.

TABLE XXII. Comparison of new and old sensitometric constants of the positive materials.

Surface	Contrast grade	Useful D max. Old	Useful D max. New	ΔD	log ES_y Old	log ES_y New	$\bar{G}_y$ New	Speed Old	Speed New
Glossy	00	1.83	1.77	0.06	1.84	1.78	0.99	200	4.0
Semi-matte	0	1.53	1.39	0.14	1.48	1.35	1.02	178	10.5
Semi-matte	1	1.54	1.46	.08	1.33	1.24	1.17	112	7.8
Semi-matte	2	1.56	1.41	.15	1.27	1.11	1.26	66.1	6.2
Semi-matte	3	1.54	1.41	.13	1.11	0.94	1.47	24.6	5.4
Semi-matte	4	1.55	1.38	.17	0.73	0.54	2.63	15.8	4.6
Glossy	0	1.63	1.49	.14	1.40	1.23	1.11	155	10.0
Glossy	1	1.70	1.57	.13	1.34	1.19	1.30	118	8.7
Glossy	2	1.71	1.58	.13	1.29	1.07	1.47	75.8	6.9
Glossy	3	1.68	1.55	.13	1.12	0.97	1.59	22.4	
Matte	1	1.35	1.12	.13	1.45	1.29	0.87	70.8	4.4
Matte	2	1.30	1.15	.15	1.30	1.13	1.01	41.7	3.5

The limiting gradient values may be deduced from the values of $\bar{G}_y$. The limiting gradient at the shadow end of the tonal scale is equal to $\bar{G}_y$, while at the highlight end of the tonal scale it is 0.1 $\bar{G}_y$. The value of $h\theta_y$ varies from 0.087 to 0.263 depending upon the contrast grade of the positive material. Thus the limiting gradient at this end of the tonal scale changes from a value less than the previous fixed gradient limit of 0.2 to a value somewhat greater. At the other end of the tonal scale, that is the shadow end, the limiting gradient values $s\theta_y$, are very much greater than those of the previously used fixed limiting gradient (0.2). It should be remembered, however, that in general the gradient in this region of the characteristic curve is changing rapidly as a function of log E_y and hence the effect upon the magnitude of the useful log exposure scale is not as great as might be expected.

It is interesting to note that the new values of speed are much less dependent upon the contrast grade than those determined by the older technique. Thus, considering the five contrast grades of semi-matte material, the old values indicate that the speed of the No. 4 grade is only about 0.1 that of the No. 0 grade. The ratio on the basis of the new technique is approximately 2, rather than 10. The relative speeds as based on the new technique are in better agreement with practice than the old ones and are a much more reliable index of the printing exposure changes required when shifting from one contrast grade to another. It should be remembered, however, that these speed values are based on the correct printing time for negatives which yield first-choice prints on each of the contrast grades. If an attempt is made to obtain the best possible print from a single negative on each of two or three contrast grades, the best printing exposure, and hence the effective relative speed values applying to this condition, will not be in strict agreement with the values as indicated in Table XXII. The attempt which is sometimes made to express the speeds of various contrast grades of developing-out papers in terms of the printing exposure required to obtain the best print on each of several contrast grades from the *same* negative leads to confusion.

TABLE XXIII. Data on prints from commercial photofinisher. Relation between useful and available maximum density.

Positive Material						
Contrast grade	No. of prints	Available D max.	Useful D max. Max.	Min.	Av.	ΔD
0	35	1.71	1.71	1.44	1.58	0.13
2	33	1.71	1.70	1.31	1.55	0.16
3	25	1.71	1.70	1.39	1.50	0.16
4	3	1.71	1.64	1.57	1.62	0.09
					Av.	0.14

Rather extensive practical tests of the validity of the numerical constants derived according to the recommended sensitometric technique have been made and we are convinced that these values are far more meaningful and of greater value in expressing the useful or effective characteristics of developing-out materials than those previously used.

VII. PRACTICAL APPLICATION

The manner in which the foregoing results can be applied in making prints by sensitometric control may now be illustrated by an example.

Assume that a negative which has not yet been used in this work is to be printed, and that the same semi-matte photographic papers that have been described in the earlier sections of this communication are available. The proper paper contrast grade and the correct printing exposure for this negative have not been obtained by the statistical print judgment method or by trial and error, but are to be determined from measured densities on the negative and the known exposure scales and speeds of the papers. The newly derived sensitometric criteria for determining speeds and useful exposure scales (see Section VI), when applied to these papers, give the values shown in Table XXII. The speed values are derived from the mid development time and consequently full advantage can be taken of the development amplitude of the positive material.

If now the negative is explored with a densitometer and found to have maximum and minimum densities of 1.10 and 0.40, respectively, the negative density scale is

$$DS_n = D_n \text{ max.} - D_n \text{ min.} = 1.10 - 0.40 = 0.70.$$

Reference to Table XXII shows that this value is not equal to the log exposure scale of any one paper, but lies between that of No. 3 and No. 4. It is, therefore, necessary to refer to the chart in Fig. 30 showing the relation between negative density scale DS_n and paper log exposure scale $\log ES_y$. It is found from this chart that the use of the No 3 contrast grade, having a $\log ES_y$ of 0.90, is indicated. This does not mean that every negative having a density scale of 0.70 will give best results when printed on the paper having a $\log ES_y$ of 0.90 rather than on a paper with a $\log ES_y$ of 0.54. It only means that on the average or statistically a higher percentage of best quality prints will result from this procedure than will be obtained by using any other known method of predicting the proper contrast grade. The print quality will usually but not always be as high as that obtainable by the more laborious method of making a number of prints on various contrast grades and selecting the best grade by careful inspection.

Having selected the particular paper to be used in printing this negative, the correct printing exposure must be determined. In Section V, it was found that for practical purposes the simple relation

$$\log E_0 = D_n \text{ min.} + \log E_s,$$

was very satisfactory for computing the desired exposure. E_0 is the printing exposure and is equal to the illumination I on the negative multiplied by the time of exposure t. E_s corresponds to the point S on the shoulder of the D-$\log E$ curve of the paper where the gradient is equal to the average gradient (see Fig. 34). It is the exposure at which the speed S of the paper is measured. If speed is defined by $S = 10^4/E_s$, the above relation may be written

$$\log It = D_n \text{ min.} + \log (10^4/S).$$

Obviously, either this relation or the former one may be used. The choice would depend on whether the speed value or the $\log E_s$ value were more conveniently available. From Table XXII it is seen that the speed for the No. 3 paper is 5.4. Then $\log E_s = 3.27$. The measured minimum negative density D_n min. is 0.40. Consequently, $\log It = 0.40 + 3.27$, or $\log It = 3.67$ and $It = 4700$ metercandle-seconds. Thus, if the illumination on the exposure plane of the printer were 470 metercandles, the exposure time would be 10 seconds. For best results the print should then be developed with sufficient safelight illumination so that the optimum development time can be determined by inspection of the print. Any slight errors that may occur in computing the exposure, measuring the illumination, or in timing the exposure, as well as any slight errors arising from lamp voltage fluctuations can nearly always be compensated for by shortening or prolonging the development time. However, the development time should not be so long as to produce appreciable fog density nor so short as to decrease the useful density scale of the paper or degrade the print quality in any way. The safe limits between which the development time may be varied without detriment to print

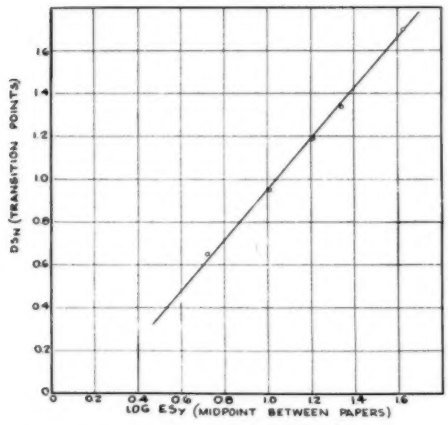

FIG. 35. Generalized relationship derived from the data in Fig. 30.

quality can, of course, be easily determined experimentally. The limits for the particular papers used in this work are discussed in Section V. The development amplitude was found to be of the order of ± 25 percent in exposure and this is equal to the exposure error that can be corrected by this procedure.

In the printing method just outlined, the chart of Fig. 30 was used for selecting the paper contrast grade. While this chart is satisfactory for the particular papers being considered, it does not give the desired relationship for other papers that may have quite different exposure scales. We therefore must consider the problem of finding a method of constructing a similar diagram for any set of papers.

An analysis of the chart in Fig. 30 shows that it possesses symmetry with respect to the point 1.2 on the log ES_y and DS_n scales. For a numerical value higher than 1.2, the density scale of the negative tends to exceed the log exposure scale of the paper, and for values lower than 1.2 the density scale of the negative tends to fall short of the log exposure scale of the paper. Hence, a negative density scale value which marks the transition from one grade of paper to the next usually does not equal the value which lies midway between the two papers. However, it can be seen that the distance from the true transition point to the point of symmetry on the DS_n scale appears to be *proportional* to the distance from the midpoint between papers to the point of symmetry. That is,

$$(DS_n - 1.2) = k[(1/2)(\log ES_a + \log ES_b) - 1.2]$$

or

$$DS_n = k(1/2)(\log ES_a + \log ES_b) + C$$

or

$$DS_n = k \text{ (midpoint between papers)} + C,$$

where DS_n is the transition point and a and b signify any two adjacent grades of paper; k and C are constants to be determined.

The validity of this relation may be tested by plotting DS_n against the midpoint between papers using the experimental data furnished by the diagram in Fig. 30. This has been done in Fig. 35. It is clear that the relation between these two quantities may be considered a linear one. The slope of the best straight line (by the method of least squares) through the plotted points, may be taken as the best value for the proportionality constant k. By this method k is found to be 1.20 and C is found to be -0.24. Thus, we have an empirical formula

$$DS_n = 1.2(1/2)(\log ES_a + \log ES_b) - 0.24$$

or

$$DS_n = 1.2 \text{ (midpoint between papers)} - 0.24.$$

It seems reasonable to assume that since this formula fits the experimental data very well it can be used in constructing any new diagram or chart for expressing the relation between negative density scale and log exposure scale for any normal set of photographic papers having any values of log exposure scale.

In deriving the numerical value of 1.20 for the constant k, the statistically determined values of log ES_y were used. If instead, the values of log ES_y determined by the sensitometric criterion had been used, as proposed in Section VI, the value $k = 1.29$ would have been obtained. For practical purposes it is proposed that k be taken as 1.25. C is then -0.30, and the empirical relation becomes.

$$DS_n = 1.25 \text{ (midpoint between papers)} - 0.30,$$

where DS_n is the point on the DS_n scale (see Fig. 30) where the transition from one contrast

grade of paper to the next occurs. The "midpoint between papers" is a point on the log ES_y scale which lies half way between the measured log exposure scales of the two papers.

This equation suggests a very simple graphical means of obtaining without computation the desired final result. Assume a set of four photographic papers differing in contrast grade whose log exposure scales have been found to be 0.60, 1.00, 1.20, and 1.50, respectively. These are then plotted as the points 1, 2, 3, 4, on the horizontal log ES_y scale in Fig. 36. The DS_n scale is numerically equal to the log ES_y, but is displaced downward by a convenient distance d. From the 1.2 point on the log E_y scale a vertical line is erected having a height equal to $4d$. The point P at the top of this line serves as a pivot for a straight edge which is made to pass through P and the midpoint between any two adjacent papers on the log ES_y scales as shown in Fig. 36. The straight edge (lines PA, PB, or PC) intersects the DS_n scale at the proper points A, B, C between the papers. The shaded triangles are then constructed using the points 1, 2, 3, 4, and A, B, C. Such a diagram can be constructed in a few minutes for any sets of papers, the log exposure scales of which have been determined. The advantage of such a diagram to anyone making prints by sensitometric control is, of course, that it reveals at a glance what paper contrast grade should be used for printing any negative of known density scale.

The experimental evidence presented in this paper is based on contact printing. The problem of printing by projection has been studied at some length but the results will not be presented in detail at this time. Several disturbing factors arise when projection printing is considered. Some enlargers employ partially collimated light, in which case the projection density of a negative is not the same as the contact printing density. The ratio of specular to diffuse density, that is, the Callier coefficient Q, is usually known for any negative material, but this does not solve the problem because the projection density of a negative usually lies somewhere between its specular and diffuse densities. Also, flare light may be present in a projection printer with the result that the illumination on the positive material is not directly proportional to the transmittance of the various areas on the negative. Another disturbing factor in some cases is the lack of perfect uniformity of illumination over the entire printing area.

These considerations do not mean, however, that the results given in this paper cannot be applied to the projection printing problem. It is quite possible to make the necessary corrections for the specularity and flare effects. A close approximation to the desired result can be obtained by calibrating the photographic paper in the particular projection printer in which it is to be used. One method is to place a photographic step tablet in the negative carrier and print this tablet by projection on each of the papers to be used. The tablet should have a Q factor similar to that of the negatives to be printed and, moreover, its average transmission relative to its minimum and maximum transmissions should be nearly equal to that of an average negative in order that the amount of flare light may be approximately normal. From the resulting prints a curve for each paper is obtained which automatically contains the

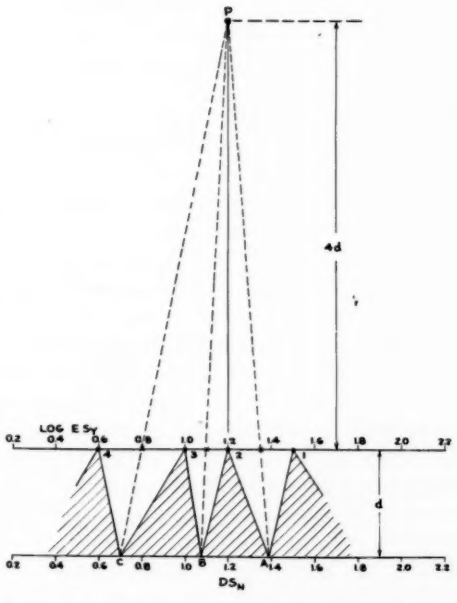

FIG. 36. A method of constructing, for any set of papers, a diagram to be used in choosing the paper contrast grade from the density scale of the negative.

corrections that are needed on the average. This characteristic curve is not actually the D-log E curve of the material, but rather the D_p-D_n relationship and this, of course, is the effective operating curve. Speed and log exposure scale can be determined from this curve by applying the sensitometric criteria derived from the contact printing procedure.

While this procedure will lead to good results in printing most negatives, it will not always give exact corrections for the specularity and flare effects. Negatives which have a relatively large or relatively small area of low density will be under- or overcorrected for flare, and negatives which are unusually dense will probably not be corrected accurately for specularity. A detailed analysis of this problem must be reserved for a later communication.

VIII. CONCLUSION

In this communication the mass of data relative to the characteristics of objects, negative materials, negatives, positive materials, and positives, including the thousands of print-quality judgments that were made during the course of the work, has been treated from a statistical point of view. Many of the conclusions drawn are based on averages and probabilities. This course was followed for a very definite reason, namely, the desire to arrive at relatively simple relationships which might be expected to apply in general, although failing under a comparatively few instances.

There is still the possibility of applying a more minute analysis to much of the available data. Moreover, we have not attempted in this paper to analyze the results from the standpoint of tone reproduction theory. We have been satisfied thus far simply to say that a panel of judges agree upon a given print as being of first-choice quality. We might very well ask the question, why is this print of first-choice quality. This probably can be answered by application of tone reproduction analysis to the first-choice prints. This further work is reserved for a later communication, the preliminary results of which indicate that some very definite requirements can be set up which must be fulfilled by a positive in order that it be considered of good photographic quality.

One of the rather striking conclusions drawn from a study of the data presented is that the maximum print density is on the average considerably below the available density of the positive material. At the other end of the tonal scale the minimum density is frequently zero and, in fact, the extreme highlight of the object is frequently forced entirely off the characteristic curve of the positive material. This situation might be interpreted to indicate that the reproduction of shadow detail is of greater importance than the reproduction of highlight detail, or that the reproduction of shadow detail is the requirement for good print quality. This may not necessarily be true and may be the result of a peculiar relationship within the tonal scale of the vast majority of exterior scenes. Thus, it is quite possible that the brightness in the tonal region which is of maximum importance from the standpoint of good photographic quality is, on the average, more closely correlated with the lowest brightness in a scene than with the maximum brightness. It is felt that a further analysis from the standpoint of tone reproduction theory will reveal the answer to this intriguing question.

ACKNOWLEDGMENT

The experimental work on which this paper was based was done by a group of research workers during a relatively long period covering at least four or five years. To give full credit to each individual for his contribution would necessitate the publication of the material under the names of several co-authors. The authors therefore owe to their co-workers in this particular case a much greater obligation than can be paid by the usual acknowledgment of assistance. The work of obtaining the negatives and the major portion of the data relative to their characteristics must be attributed to Mr. H. R. Condit. Mr. L. D. Clark was in charge of the important work of making the prints with precise sensitometric control. The reading of the gray scale densities and the plotting of the curves for the choice prints were carried out by Mr. Howard Ott. To Mr. C. D. Edgett, chiefly, must go the credit for the accurate reduction of the enormous amount of numerical data to

tabular form and the preparation of the drawings and graphs. Mr. W. H. Carnahan gave valuable advice in the interpretation of the results and with Mr. C. Amadio assisted in the work from time to time. Each of these men deserves high praise for initiative and originality in solving many difficult problems which arose in the experimental and analytical work.

The authors wish also to express their most hearty thanks and appreciation to all those who so willingly gave time and careful attention to making the judgments of print quality.

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Ultraviolet Rotatory Power of Crystalline Nickel Sulfate at the Temperature of Liquid Oxygen

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(Received July 25, 1942)

CRYSTALLINE nickel sulfate α-hexahydrate was shown by Beevers and Lipson[1] to belong to an enantimorphic pair of space groups and hence to be capable of optical activity. They also noted qualitatively that the rotation was anomalous. Recently a quantitative study of the optical activity of the crystal has been made. The dispersion of the natural rotatory power has been observed throughout the visible,[2] the ultraviolet,[3,4] and the infra-red[4] regions and it was found that the crystals were optically inactive for light of 0.503μ and that the rotation of the plane changes sign when passing through this wave-length. This change of sign is a result of a large anomaly in the rotatory power associated with infra-red absorption at 1.16μ; progressively smaller anomalies arise from other absorption bands at 0.69μ and 0.385μ.

The effect of lowered temperature upon the rotatory power has recently been determined for the visible spectrum;[5] the change found is approximately 1° per mm at the temperature of liquid oxygen. This paper summarizes an extension of such measurements through the ultraviolet; the experiments are more fully described elsewhere.[6]

APPARATUS AND EXPERIMENTAL METHOD

A previously described photographic measurement technique[4,7] was used in which light from a quartz mercury arc entered a Bausch and Lomb double prism monochromater where the desired wave-length was selected. This ray then passed through a Glan-Thompson polarizing prism, the cooling device, the crystal, a Wollaston double image prism, and fell on a photographic plate. Two narrow images of the monochromater slit appeared on the film. The relative densities of the two images were measured with a microphotometer and a curve plotted for density *vs.* rotation to determine the rotation necessary to make the density of the two images equal.

The crystal was cooled by a modification of a method described by Molby[8] which avoided the immersion of the crystal directly into liquid oxygen as was the method used in preliminary work.[5] Figure 1 gives a schematic diagram of the apparatus. The entire apparatus is mounted upon

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[1] C. A. Beevers and H. Lipson, Zeits. f. Krist. **83**, 123–138 (1932).
[2] N. Underwood, F. G. Slack, and E. B. Nelson, Phys. Rev. **54**, 355 (1938).
[3] P. Rudnick and F. G. Slack, Phil. Mag. [7] **28**, 241 (1939).
[4] L. R. Ingersoll, P. Rudnick, F. G. Slack, and N. Underwood, Phys. Rev. **57**, 1145 (1940), for earlier references.
[5] P. Rudnick, F. G. Slack, and J. J. O'Conner, Phys. Rev. **58**, 1003 (1940).
[6] W. C. Gilmore, Jr., "Ultraviolet rotatory power of crystalline nickel sulfate at the temperature of liquid oxygen," Thesis, Vanderbilt University (1941).
[7] J. J. O'Conner, "Magnetic rotatory power of crystalline nickel sulfate α-hexahydrate in the ultraviolet region," Thesis, Vanderbilt University (1940).
[8] F. A. Molby, Phys. Rev. **31**, 291 (1910).

a brass base which is attached to the lathe-bed holding the polarimeter. *A* and *A'* are two fused quartz vacuum cells with flat end windows. The end of each cell extends beyond the cold brass tube *D*, thus remaining warm and avoiding frosting. *B* is glass wool insulation covered with adhesive tape.

The two brass T tubes, *C* and *D*, form the outer and inner walls of a cooling jacket the horizontal ends of which are covered with flexible thin brass

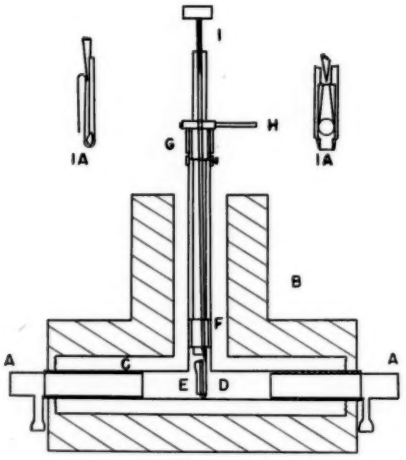

FIG. 1.

sheet. Liquid oxygen is poured into the open end of tube *C*. The crystal holder *E* consists of a long tube with bearings *F* and *G* which hold it in good alignment. The crystal is mounted at the lower end upon a metal plane surface which has been folded over as indicated in Fig. 1*A* to permit some motion of the crystal. A 6-mm hole, drilled through the plate, enables the ray of light to traverse the crystal. Two small brass wires hold the crystal in place. The handle *H* attached to the crystal holder is used to orient the crystal about the vertical axis. When the correct position is ascertained, a stop, attached to the vertical tube *D* is set so this position may be duplicated without difficulty. Orientation of the crystal about the horizontal axis is accomplished by rotating the plunger *I* up and down. The lower tapered end of the plunger extends under the upper end of the movable brass plate to which the crystal is attached. This permits rotations about a transverse horizontal axis. The position of the crystal is such that it is entirely surrounded by cold surfaces except for the fused quartz windows which subtend a solid angle of only one-half of one percent of 4π.

Visual and photographic tests of the windows of cells when evacuated indicated that they were optically inactive.

Measurements of the temperature of the crystal were made with an alumel-chromel-alumel thermal couple. No difference in the indications of the thermal couple could be detected when the crystal and holder were removed from their normal position and immersed directly in liquid oxygen. The indication of another known point, the melting point of CS_2, was observed. Extrapolation of the calibration curve to these points indicated a roughly linear calibration. Therefore, the temperature is believed to be within ten degrees of 90° Kelvin.

In view of the fact that the changes in rotation were small, these changes were observed as directly as possible by the following procedure. The first half of each film was devoted to exposures at room temperature with the crystal in the light path, while the second half was used for similar photographs at low temperature. Four exposures were taken for each wave-length at room temperature. The crystal was then cooled to the temperature of liquid oxygen and the process repeated. Match points at room temperature and at low temperature were found. The difference between these was the change in rotation caused by the temperature change. Also

TABLE I.

Wave-length	Rotatory power at 90°K minus rot. power at room temp.	Av. deviation of individual measurements from mean	Published value of rot. power at room temp (reference 4)
2536A	−1.4°/mm	0.6°/mm	+18.4°/mm
2804	−1.6	0.3	+11.4
3130	−1.3	0.2	+ 6.9
4358	−1.3	0.1	+ 1.7
Previous visual and photographic data*			
4358	−1.1		
5461	−1.2		
5893	−1.3		

* Data supplied by correspondence prior to publication and appearing in following paper by P. Rudnick and L. R. Ingersoll, J. Opt. Soc. Am. **32**, 622 (1942).

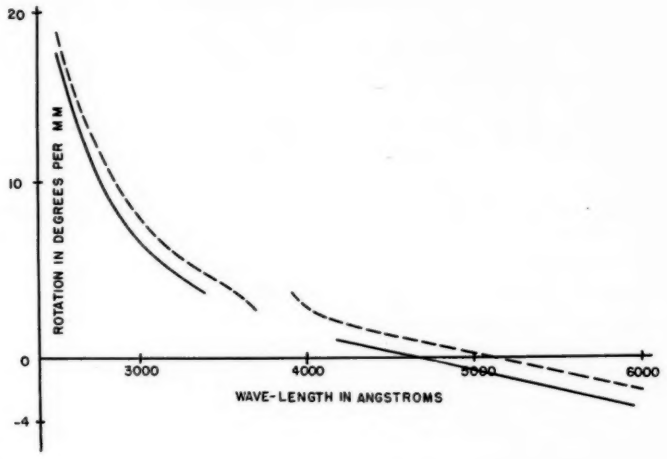

FIG. 2.

some match points were taken with no crystal which gave values for total rotatory power of the crystal which agreed satisfactorily with published data.

A STATEMENT OF RESULTS

During the course of the investigation both dextro- and laevo-rotatory crystals were used to obtain data on the temperature effect. The change in rotation with temperature was measured for each crystal at each of four wave-lengths. Results are given in Table I.

Figure 2 gives the natural rotatory dispersion curve for the crystal at room temperature throughout the visible and ultraviolet regions as plotted from published data.[4] The curve running parallel to the continuous line represents the natural rotatory dispersion curve for the crystal at the temperature of liquid oxygen as plotted from data in Table I. The break in the curve represents the position of an absorption band.

Thus the difference in rotatory power due to temperature change appears practically constant throughout the visible and ultraviolet regions.

Natural Rotatory Power of Nickel Sulphate at Low Temperature

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(Received July 25, 1942)

THE crystalline alpha-hexahydrate of nickel sulphate has a natural optical rotatory power which has been measured for wave-lengths from 0.25μ to 2.2μ at room temperature.[1] Strong anomalous dispersion and the associated absorption and circular dichroism appear in the near infra-red region. This paper and the one immediately preceding[2] report a complete repetition of these observations at the temperature of liquid air or oxygen. Preliminary measurements[3] had shown the rotatory power to be considerably changed at these low temperatures.

EXPERIMENTAL METHODS

Near infra-red measurements at liquid-air temperatures were carried out at the University of Wisconsin by means of double-image polarizing prisms, a prism spectrometer, and a differential thermopile, in a manner previously described.[1] Some supplementary visual measurements were made at Vanderbilt University, using liquid oxygen, by means of a Schmidt and Haensch precision polarimeter, using as sources a sodium flame, and a mercury arc lamp, from which two lines were isolated with Jena filters.

Crystal specimens were cooled by the means described in detail by Knopf and Gilmore,[2] briefly a double-walled container in which a crystal could be almost entirely surrounded with liquid air or oxygen though not brought into contact with it, with the radiation entering and leaving through evacuated quartz cells. Liquid air, rather than liquid oxygen, was used as a cooling agent in the infra-red work. A small uncertainty was contributed by the fact that the temperature of the specimen was raised slightly—not more than one degree, as indicated by measurements with a fine thermocouple applied directly to the face of the crystal—by the radiation. Taking into account these and other considerations the lower temperature is taken as 85°K±2°. The low temperature (obtained with liquid oxygen) employed at Vanderbilt is probably at least as precisely fixed. While room temperature was not under control it varied little from 25°C (290°K). The error resulting from this one percent uncertainty in temperature is slightly less than the probable error of the other measurements.

In most cases measurements were first taken at room temperature. The specimen was then cooled without changing its position and the measurements repeated. It was hoped in this way to obtain differences which would be independent of certain errors possible in the separate measurements.

MEASUREMENTS

Table I contains our new data for the visible and infra-red regions, and also quotes the results of Knopf and Gilmore[2] in the ultraviolet. These three groups of data are discussed in order of increasing wave-length in the following paragraphs.

The experimental results on the change of rotatory power with temperature in the ultraviolet are reported by their authors[2] in the form of differences and are restated in column (3), Section (a) of Table I. These differences are regarded as independent of wave-length within experimental error. Column (2) gives rotatory powers in the ultraviolet based on these differences and previously published values[1] at room temperature.

The observations in the visible region repeated some earlier preliminary measurements,[3] under improved optical conditions, i.e., with flat windows and air, rather than cylindrical tubes and liquid oxygen, in the line of sight. The experimental values for the differences in rotatory

[1] L. R. Ingersoll, P. Rudnick, F. G. Slack, and N. Underwood, Phys. Rev. **57**, 1145 (1940).
[2] W. C. Knopf, Jr. and W. C. Gilmore, Jr., "Ultraviolet rotatory power of crystalline nickel sulfate at the temperature of liquid oxygen," J. Opt. Soc. Am. **32**, 619 (1942).
[3] P. Rudnick, F. G. Slack, and J. O'Connor, Phys. Rev. **58**, 1003 (1940).

TABLE I. Low temperature optical data for nickel sulphate.

(1) Wave-length in microns	(2) Rotatory power at −188°C,* degrees per mm	(3) Difference, Col. (2) −rot. power at room temp.	(4) Ratio, Col. (2) to rot. power at room temp.	(5) Difference, rot. power by Eq. (2) −Col. (2)	(6) Circular dichroism at −188°C in degrees of ellipticity per mm	(7) Ratio, Col. (6) to dichroism at room temp.	(8) Difference, dichroism by Eq. (1) −Col. (6)	(9) Absorption, coefficient, per mm	(10) Difference Col. (9) −abs. coeff. at room temp.
Section (a)									
0.2537	+17.0	−1.4		−0.2					
0.2804	9.8	−1.6		+0.25					
0.3130	5.6	−1.3		+0.25					
0.4358	0.4	−1.3		+0.15					
Section (b)									
0.4358	+0.6	−1.1		−0.05					
0.5461	−2.0	−1.2		+0.2					
0.5893	−2.9	−1.3		+0.3					
Section (c)									
0.55	−2.1	−1.20		+0.3	—	—	—	0.4	0.0
0.60	−3.4	−1.55		+0.7	0.65	1.4	+0.05	1.8	0.0
0.63	−3.45	−1.25		+0.6	—	—	—	—	—
0.65	−3.25	−1.10		+0.6	1.6	1.2	−0.01	2.7 (max.)	−0.7
0.66	—	—		—	1.65 (max.)	1.2	0.00	—	—
0.70	−3.1	−1.3		+0.95	1.4	1.0	0.00	2.3	−1.1
0.75	−3.3	−1.6		+0.85	0.7	0.7	−0.05	1.1	−1.2
0.80	−4.6	−2.3		+1.1	0.3	0.7	−0.07	0.5	−0.6
0.85	−6.0	−2.7		+1.3	0.6	1.7	−0.40	0.5	−0.2
0.90	−7.6	−3.0		+1.0	1.4	2.7	−0.73	0.8	−0.1
0.95	−9.5	—	1.61	+0.7	3.1	1.9	−0.75	1.2	−0.2
1.00	−10.8 (max.)		1.55	+0.3	6.6	1.8	−0.66	1.9	−0.2
1.02	−10.7		1.52	+0.1	—	—	—	—	—
1.05	−9.8		1.46	0.0	10.4	1.55	+0.68	2.4	−0.3
1.10	−5.8		1.29	+0.2	14.7	1.52	+1.68	2.8	−0.3
1.14	—		—	—	17.0 (max.)	1.48	−0.28	—	—
1.15	0.0		—	+0.9	—	—	—	3.0 (max.)	−0.3
1.20	+6.3		1.80	+0.5	13.3	1.30	+1.12	2.9	−0.4
1.25	10.0		1.80	−0.2	8.8	1.2	+0.90	2.2	−0.8
1.265	10.2 (max.)		1.70	−0.2	—	—	—	—	—
1.30	9.8		1.53	−0.1	5.8	1.2	−0.75	1.5	−1.0
1.35	8.7		1.47	−0.6	2.9	1.0	−0.61	1.1	−0.9
1.40	7.6		1.49	−1.2	1.6	0.9	−0.64	1.3	−0.6
1.45	6.1		1.43	−1.0	0.8	0.8	−0.39	1.7	−0.6
1.50	4.9		1.42	−0.7	0.3	0.5	−0.10	1.9	−0.6
1.60	3.3		1.40	−0.2	—			1.8	−0.4
1.70	2.5		1.39	−0.1				1.3	−0.7
1.80	2.0		1.43	−0.1				0.8	−0.7
1.90	1.7		1.48	−0.1				2.4	−0.8
1.98	—		—	—				8.8 (max.)	0.0
2.00	1.5		1.58	−0.1				—	—
2.10	1.2		1.50	0.0				4.2	−0.5
2.20	1.0		1.54	0.0				2.2	−0.7

* For Sections (a) and (b) this temperature is −183°C.

power between room and low temperatures, appearing in column (3), Section (b), are regarded as a little more reliable than the measurements at either temperature alone. The agreement with the preliminary measurements is satisfactory except at 4358 A.U., where a change with temperature of only 0.5°/mm was at first reported. This is evidently low and should be discarded in favor of the value in Table I. The new measurements at room temperature (not tabulated) agreed with the published data[1] at room temperature.

All the data in Section (c) are points read from smooth curves drawn through numerous plotted experimental points. The new data on both rotatory power and dichroism at room temperature agreed so closely with the published values[1] that no further reference has been made to them. The smoothed experimental data at low tempera-

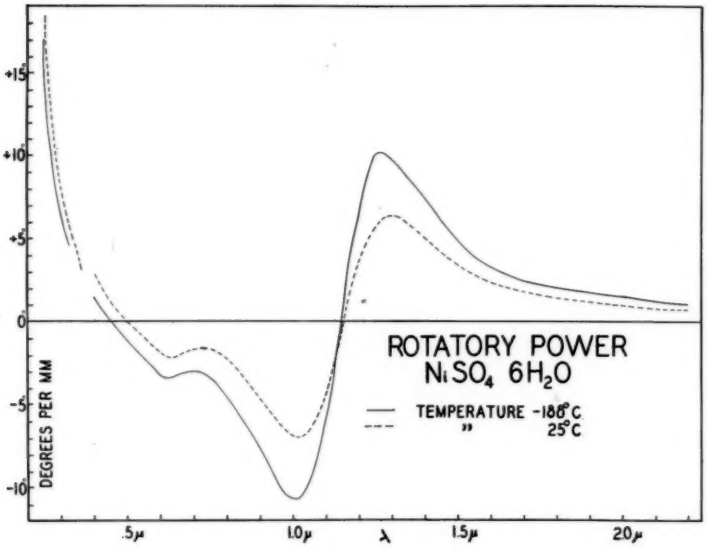

FIG. 1. Effect of low temperature on rotatory power of nickel sulphate.

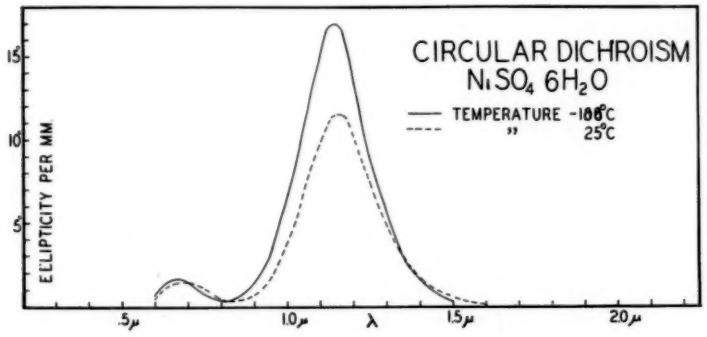

FIG. 2. Effect of low temperature on circular dichroism in nickel sulphate.

ture are reported directly in columns (2) and (6). Columns (4) and (7) contain comparisons with the published room temperature values by means of ratios rather than differences.

The new measurements of absorption coefficients at room temperature showed some differences from the published values, so here, too, greater reliance was put on the observed changes with temperature, rather than on absolute values. They are reported in column (10). The absorption coefficients in column (9) are again based on the differences in column (10) and the published room temperature data.[1] A particularly favorable comparison of absorption at the two temperatures in the very intense water band at 1.98μ was obtained with a very thin crystal plate, 0.082 mm in thickness.

The crystal specimens used, aside from the one just mentioned, varied in thickness from about 0.4 to 0.9 mm. The visual data are averages for three specimens; over a dozen, altogether, were used in the infra-red.

Figures 1 to 3 show the low temperature data of Table I in graphical form, with the corresponding room temperature curves for comparison. The temperature effect is sufficiently

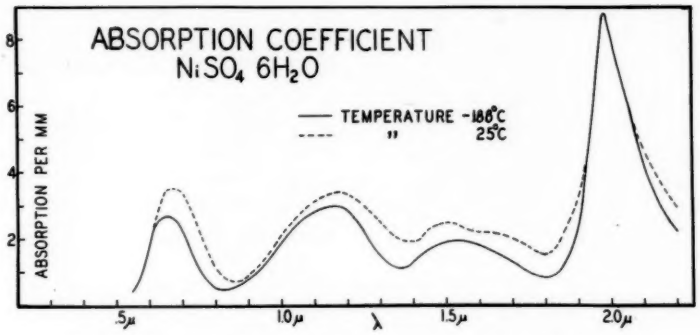

FIG. 3. Effect of low temperature on absorption in nickel sulphate.

small in the ultraviolet and visible regions to warrant neglect of the distinction between liquid-air and liquid-oxygen temperatures.

DISCUSSION OF RESULTS

The effect of low temperature on the circular dichroism can be summarized by saying that the principal maximum at 1.15μ is about 8 percent narrower and 50 percent higher at the lower temperature, the increase in area under the curve, measuring the rotatory strength, being about 37 percent. The peak at 0.69μ has shifted slightly, to 0.67μ, and is about 8 percent narrower and 10 percent higher. The changes in the rotatory power arise almost entirely from the altered contributions of these two bands. There is no indication of change in the slight anomaly at 0.385μ, and there is an apparent 4 percent decrease in the rotatory power contributed by far ultraviolet absorption, perceptible only at the extreme short wave-length end of the observed curve. The dissymmetry factor (relating difference in absorption for the two senses of circular polarization to total absorption) for the 1.15μ band[1] is increased from the already high value of 0.24 to 0.40.

TABLE II. Effect of low temperature on optical activity.

$\alpha-NiSO_4\,6H_2O$	Percentage change in rotatory power (referred to that at room temp.) at liq. air temp.
Contribution from absorption around 1.15μ	37%
Contribution from far ultraviolet absorption	− 4%
Quartz	− 2%
Cinnabar (at 0.644μ)	−20%
Sodium chlorate	−12%*

* Extrapolated from 0°C to 150°C measurements.

This summary of the temperature effect is based on mathematical expressions constructed to represent numerically the low temperature data on dichroism and rotatory power. The procedure followed, and the mathematical functions and notation used, were identical with those employed in the presentation of the room temperature data,[1] to which reference is made for fuller discussion. In the notation there defined, the best numerical representation of the low temperature data which has been secured is the following:

$$\epsilon=\frac{1.15}{\lambda}\left\{13.7\exp\left[-\left(\frac{\lambda-1.15}{0.135}\right)^2\right]+3.4\exp\left[-\left(\frac{0.87-\nu}{0.125}\right)^2\right]\right\}+\frac{0.67}{\lambda}1.66\exp\left[-\left(\frac{1.492-\nu}{0.176}\right)^2\right], \quad (1)$$

$$\alpha=\frac{n^2+2}{n_0^2+2}\left[\alpha_\lambda(13.7,\ 1.15,\ 0.135)+\alpha_\nu(3.4,\ 0.87,\ 0.125)+\alpha_\nu(1.66,\ 1.492,\ 0.176)+\frac{0.009}{\lambda^2-0.150}+\frac{0.55}{\lambda^2-0.035}\right]. \quad (2)$$

Table II shows variation of rotatory power with temperature for quartz,[4] cinnabar,[5] and sodium chlorate[5] as compared with nickel sul-

[4] International Critical Tables, 6: 343.
[5] International Critical Tables, 7: 353.

phate. The greatest temperature sensitivities occur in the infra-red "anomalous" portion of the $NiSO_4$ rotatory power curve and in cinnabar whose rotatory dispersion is also anomalous, probably controlled by its visible absorption. The ultraviolet part of the $NiSO_4$ rotatory power curve whose dispersion is normal, and the quartz curve, also normal, are, in contrast, much less temperature sensitive. $NaClO_3$, with normal dispersion, is intermediate in temperature sensitivity. We thus see a tendency, at least, for rotatory power to show increasing variation with temperature when the associated absorption occurs at longer wave-lengths.

In conclusion we wish to acknowledge our indebtedness to Mr. J. N. Humphrey and to the Wisconsin Alumni Research Foundation for assistance.

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Luminescent Pigments and Coatings*

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(Received August 11, 1942)

INTRODUCTION

MANY materials exhibit luminescence over a wide range of conditions of excitation. This discussion is limited to the practically useful organic dyes and inorganic pigments of today which are activated by radiant energy in the short wave-length visible and near ultraviolet spectral range. Such luminescent materials in the past years have been little known and mysterious novelties used only by magicians, conjurers, and stage artists. Today they are finding many practical applications where scotopic vision must be used and maintained.

Fluorescence is the term generally applied to the visible energy emitted during activation. Phosphorescence is the term generally applied to the visible energy emitted after the exciting light source is extinguished. In their practical use today, fluorescent materials are defined as those having no useful afterglow. Phosphorescent materials are those having a useful afterglow of at least a few minutes' duration and generally from two to twelve hours or more.

FLUORESCENT COATINGS

The most brilliant and colorful fluorescent materials are organic dyes such as rhodamine or eosine. They are most effective when applied to textile fibers or dissolved in lacquer or similar vehicles. Such dyes are generally not light fast and their use is limited to indoor applications. Greater light fastness is obtained by applying the dyes to an inorganic base to form a lake pigment. In general, the fluorescent color and the daylight color of such organic dyes is about the same. While a wide range of colors is available, the choice of these dyes is limited due to their lack of solubility in non-aqueous media.

Metallo-organic compounds, such as the zinc salt of 8-hydroxyquinoline, are somewhat more weather resistant. They are highly fluorescent, but fluorescent color does not generally correspond to daylight color. Both the response to activation and the extinction after activation ceases are instantaneous.

Organic fluorescent materials have been used in dyed plastics, textiles, paper fibers, lacquers and printing inks, and powders. Unusual decorative effects have been obtained, and their use in this connection will be increased with the present dimout on the eastern seaboard. Paper made of dyed fibers or printed with fluorescent inks makes counterfeiting difficult. Laundry marking, identification marking, crime detection, use in preparation of plates for color printing of maps, and detection of surface flaws or imperfections in machined objects are examples of practical uses.

The fluorescence of a number of inorganic materials is well known. Such natural minerals as willemite, calcite, or fluorite are examples. The inorganic pigments most commonly used in fluo-

* Paper presented at Symposium on Fluorescence and Phosphorescence of the Optical Society Meeting held at the Massachusetts Institute of Technology, Cambridge, Massachusetts, July 21, 1942.

rescent coatings are zinc sulfide and combinations of zinc and cadmium sulfide. These pigments are relatively fine in particle size and are comparable to regular zinc sulfide and cadmium sulfide pigments in their paint-making properties. A limited range of colors from green to red is available and fluorescent color generally does not match daylight color. In some vehicles and under certain conditions of exterior exposure, these pigments are subject to a darkening action with resultant loss in fluorescent intensity. However, they are generally quite stable and will withstand considerable exterior weathering. There is some lag in response to activation and also in extinction after activation ceases.

Inorganic fluorescent pigments have been used in plastics, paints, and inks. Dials, charts, maps, and printed matter, requiring weather and sunlight resistance, are prepared for use by airplane pilots, bombardiers, speed boat pilots, or other machinery operators where maximum visibility and legibility are required without affecting the dark adaptation of the users' eyes.

The optical characteristics of fluorescent materials that are of greatest interest are the reflection color, the fluorescent color and brightness, and the rate of extinction after activation ceases. Standard methods of spectrophotometry are generally applicable and both reflection color and fluorescent color are expressed in terms of dominant wave-length, purity, and reflectance or brightness. The fluorescent brightness will range from 5 microlamberts to 3000 microlamberts or more, depending upon the type of fluorescent material and the intensity of the activating source. The brilliant and colorful organic materials are used at relatively high levels of brightness from 500 to several thousand microlamberts. The inorganic fluorescent materials are most often used at relatively low levels of brightness in the range of from 5 to 40 microlamberts. Since these materials are used primarily to permit reading and identification without the loss of dark adaptation, the brightness must necessarily be kept in the low part of the range.

PHOSPHORESCENT COATINGS

The property of phosphorescence is generally limited to inorganic, highly crystalline materials. Some natural minerals, such as certain willemites, exhibit this property. The pigments in most common use today are crystalline forms of zinc, cadmium, strontium, and calcium sulfide; zinc and cadmium sulfide combinations are used and combinations of calcium and strontium sulfide are also employed. Such pigments are very coarse and luminescent properties are dependent upon their coarse crystalline nature. The particle size of such pigments will range from 5 to 20 microns. Since their particle size is so much greater than that of normal pigments, they offer considerable difficulty of fabrication in paints or other luminescent coatings. The texture and smoothness will be poor, hiding or covering power will be low, and the pigments will settle badly if incorporated into the vehicle and allowed to stand before using. Such pigments cannot be ground on a paint mill but must simply be mixed or stirred into the vehicle since mechanical work causes them to lose a substantial part of their phosphorescence. The color of such pigments in visible light is generally a dull white with a gray or yellow tinge. The color of the phosphorescence varies from a deep purple to an orange, depending upon the type of pigment.

The zinc and cadmium sulfide pigments are characterized by high intensity immediately after activation ceases but by a comparatively rapid loss in intensity. The useful afterglow is generally from thirty minutes to about two hours. An appreciable time of activation is required to reach full intensity, this time varying from ten seconds to a minute or more. Phosphorescent colors range from green to orange. Such pigments are relatively stable and can be used in many normal paint vehicles. They are reasonably weather-resistant and may be used outdoors with only partial loss in phosphorescent properties over a period of a year or more. Under some conditions of exterior exposure, there is a tendency for the zinc and cadmium sulfide pigments to darken with accompanying loss of phosphorescence.

The calcium and strontium sulfide pigments have a somewhat lower intensity immediately after activation ceases but lose intensity more slowly than the zinc and cadmium sulfides. The useful afterglow may be from three to ten hours or more. Activation time to reach full intensity is long, varying from one to ten minutes. Phospho-

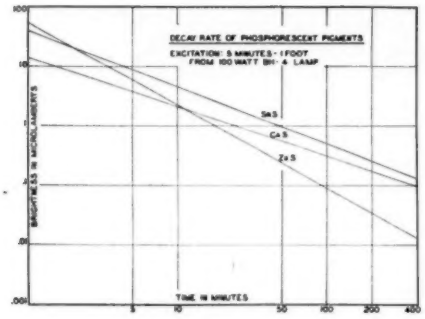

FIG. 1.

rescent colors range from purple to greenish blue. Calcium and strontium sulfide pigments are somewhat unstable in the presence of moisture or acids. They must therefore be used only in vehicles carefully selected for freedom from such ingredients. In addition, the films prepared from calcium and strontium sulfide pigments must be protected from atmospheric moisture or, in the case of exterior exposure, from rain, by a protective film, usually a film of the clear vehicle, a film of plastic, or a sheet of glass. When given adequate protection from moisture, these pigments are capable of withstanding exterior exposure for some months.

Phosphorescent pigments have been used in both plastics and paints to prepare various types of phosphorescent coatings. The zinc and cadmium sulfide pigments have been used where their stability, weather resistance, and high initial intensity are of value and where a short period of afterglow is permissible. Plastics containing zinc sulfide pigments have been used for the preparation of jewelry, novelties, and marking tapes. Tapes, signs, and cloths for the marking of exits and areas where rapid evacuation may be required in the event of power failure have been prepared from these pigments. Where long afterglow is essential, such as in continuous use over a period of some hours during blackouts, the calcium and strontium sulfide pigments have been used. Methacrylate and polystyrene plastics as well as methacrylate, alkyd resin, and polystyrene resin vehicles afford satisfactory vehicles for the calcium and strontium sulfide pigments and permit the preparation of coated papers, coated cloths, decalcomanias, paints, and molded resin shapes. Such preparations have been used in the fabrication of religious and other novelties, armbands, capes, traffic markers, signs, tapes, markings for obstructions, roads, shelters, and the like.

The optical characteristics of phosphorescent materials that are of greatest interest are the initial phosphorescent brightness and the rate of decay. Color is generally of secondary importance at the low brightness levels involved. Initial brightness values (intensity one minute after activation) range from approximately ten to eighty microlamberts. One hour after activation, the best materials are down to about one microlambert, or less and under most conditions of use, the phosphorescent brightness is in the range of from 0.01 to 1.0 microlambert.

The measurement of low brightness in this range may be accomplished by the use of several types of low brightness meter. Visual meters have been described by Taylor[1] in the British Standard Specification BS/ARP 18 and by C. E. Barnett.[2] The so-called wide angle photometer described by Barnett is a visual instrument making use of a photometer bar and diffusing screen with a series of color filters and neutral tint filters. Such an instrument is calibrated against a standard lamp to provide readings in absolute units and is found to give reasonably accurate results in the range down to 0.01 microlambert. Measurements with a visual photometer of this type are made with the eye varying in light or dark adaptation, according to the brightness of the luminescent material being measured. Brightnesses are therefore the effective brightness seen by the eye expressed in terms of the light adapted eye.

Decay curves of characteristic phosphorescent sulfides, obtained on the Barnett wide angle visual photometer, are shown in Fig. 1. Barnett finds the brightness of a white traffic paint on a clear, starlit night in March to be 0.12 microlambert. Zinc sulfide will decay to this value in approximately 70 minutes, calcium sulfide in three hours, and strontium sulfide in four hours. When used outdoors, under conditions approximating starlight, the materials are therefore only useful for about four hours. When used indoors, or under conditions of total darkness, they may be useful for eight to twelve hours or more.

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[1] A. H. Taylor, Trans. Am. Illum. Eng. Soc. **37**, 19 (1942).
[2] C. E. Barnett, "Properties of luminescent materials," News Edition, Ind. Eng. Chem. p. 1006 (August 25, 1942).

Proceedings of the Summer Meeting of the Optical Society of America

Massachusetts Institute of Technology, Cambridge, Massachusetts

July 20–22, 1942

THE first Summer Meeting of the Optical Society of America, held concurrently with the M.I.T. Spectroscopy Conference, July 20–22, 1942, to celebrate the tenth anniversary of the Spectroscopy Conferences, was most successful. The meetings were well attended, more than 300 persons being registered.

Program of Spectroscopy Conference

A Decade of Spectroscopy Conferences, G. R. Harrison, *Chairman.*

Ten Years' Progress in Spectrochemical Analysis, W. F. Meggers, *National Bureau of Standards.*

Spectroscopy in World War I, Keivin Burns, *University of Pittsburgh.*

On Precision in Spectrochemical Analysis, H. B. Vincent, *University of Michigan (with R. A. Sawyer).*

Sparking Technique and Spectrographic Steel Standards, B. F. Scribner, *National Bureau of Standards (with C. H. Corliss).*

Plate Calibration Problems, R. A. Sawyer, *University of Michigan (with H. B. Vincent).*

The Training of Industrial Spectroscopists, Mary Warga, *University of Pittsburgh.*

Some Observations on the Use of Powders in Spectrochemical Analysis, A. E. Ruehle, *Bell Telephone Laboratories.*

Search for New Sources of Strategic Metals by Use of the Spectrograph, L. W. Strock, *Saratoga Springs Commission.*

Progress in the Theory and Use of Concave Diffraction Gratings, H. G. Beutler, *University of Chicago.*

Spectrochemical Determination of Silicon, Iron, and Aluminum in Mineral Powders, J. W. Ballard, *United States Bureau of Mines (with H. I. Oshry and H. H. Schrenk).*

A Micro-Method of Chromatographic Analysis of Material in Preparation for Spectroscopic Analysis—A Demonstration, M. O'L. Crowe, *New York State Department of Health (with A. Walker).*

Relations Between Structure and Absorption Spectra of Organic Compounds, W. R. Brode, *Ohio State University.*

The Significance of Stray Light in Photoelectric Filter Photometers, M. N. States, *Central Scientific Company (with J. C. Anderson).*

Spectrographic Control in the Preparation of Hydrocarbon-Protein Conjugates, R. N. Jones, *Harvard University (with H. J. Creech of the University of Maryland).*

Direct Spectrographic Determination of Copper and Manganese in Dyestuffs, G. L. Buc, *American Cyanamid Company (with G. L. Royer and A. R. Norton).*

The meeting of the Optical Society began with the session on Tuesday afternoon, at which four speakers discussed the subject of Fluorescence and Phosphorescence. The titles of these invited papers are listed below.

Symposium of Invited Papers on Fluorescence and Phosphorescence

The Theory of Luminescent Materials, F. Seitz, *University of Pennsylvania.*

Activating Light Sources for Fluorescent and Phosphorescent Materials, E. W. Beggs, *Westinghouse Electric and Manufacturing Company.*

Fluorescent and Phosphorescent Pigments and Coatings, G. F. A. Stutz, *New Jersey Zinc Company.*

Cathodoluminescent Materials, H. W. Leverenz, *RCA Manufacturing Company.*

In his paper, Dr. Seitz made an elementary and very clear presentation of the theory of luminescent materials. Mr. Beggs discussed and demonstrated activating light sources for fluorescent and phosphorescent materials. He divided lamps into four main types; filament lamps, glow lamps, mercury vapor lamps, and fluorescent lamps. Two new and particularly interesting lamps were demonstrated, a small RP 12 bulb in 3-watt, 12–16 volt, or 4-watt, 24–28 volt d.c., used to illuminate airplane dials for night flying, and a fluorescent lamp in 6, 15, 30, or 40 watts, with 360 BL phosphor, a new phosphor radiating principally ultraviolet. He also showed a general lighting unit capable of flooding large factory areas with enough ultraviolet so that, in case of emergency blackouts, exit signs and direction lines on the floor of a plant would be sufficiently activated to allow prompt evacuation. This is a 3000-watt type of high brightness.

Dr. Stutz discussed and demonstrated fluorescent and phosphorescent pigments and coatings made by the use of organic dyes and inorganic pigments. The organic dyes provide a wide color range and brilliant intensities, but are not light-fast, their fluorescent and daylight colors being generally similar. The inorganic pigments

have a narrower color range, their daylight and fluorescent colors are often dissimilar, but they possess greater light fastness. The strontium, calcium, and zinc sulfides provide practical phosphorescent coatings for which intensity measurements and rates of decay were presented. Dr. Stutz' paper appears in this issue of the Journal.

Dr. Leverenz introduced his discussion of cathodoluminescent materials by a history of luminescent studies. Results of investigations of many structures were discussed to indicate how unwise it may be to predict the color of new compounds according to any preconceived notion of how the elements of the periodic table are combined in the phosphors. Results of some of these investigations will appear shortly in tabular form in the *RCA Review*. Materials were demonstrated that fluoresce intensely under 3650A, but show little fluorescence under 2537A, and vice versa. A new silicate material has been found that is as stable as the sulfides, but its formula is available for military use only.

Informal Dinner

On Tuesday evening about 200 persons attended an informal dinner at the Hotel Commander. Professor Harrison, as toastmaster, called the roll of attendance at previous conferences. He found that many were attending the spectroscopy conferences for the first time, quite a number for the second and third, from five to ten each for the sixth, seventh, eighth, and ninth times. A few had been present at all ten conferences.

A photograph of the first conference, with 65 in attendance, showed the growth of the summer gathering since 1933. Dr. Harrison then gave a brief and amusing resumé of "highlights" of the ten conferences. Professor Worthing, President of the Optical Society, welcomed the large group of new Optical Society members present, after which Dr. Duffendack gave one of his "annual reports," and Dr. Burns reminisced a bit about past meetings. Dr. Meggers aroused great interest with his discussion of "forgotten spectroscopists," most important of whom was Charles Porter Snyder, who published "The wave number system of rhodium" in 1901 in the *Astrophysical Journal*. Twenty-five years later his data were proved to be without error. All efforts to locate the author or discover anything regarding the present whereabouts of this spectroscopist who was "born too soon" had been unsuccessful. The place of his birth had been found to be Hackettstown, New Jersey, and the date June 22, 1868. Later in the evening Dr. Meggers was given information which indicated that Snyder may still be living and may yet be found.

The evening was completed by a quiz game, which started with a quiz of Dr. Meggers regarding tin (for the tin'th anniversary!) and ended with a general double-or-nothing quiz of audience teams in which the final score gave the Infra-reds a slight edge over the Ultraviolets.

Contributed Papers

Fifteen papers of general optical interest were presented at the sessions on Wednesday. The authors' abstracts of these papers are appended.

Program of Sessions for Contributed Papers

(Titles and Abstracts of Papers)

1. Propagation of Electromagnetic Waves in a System of Parallel Layers of Isotopic Substances. R. K. Luneburg, *Spencer Lens Company.*

The experimental progress which has been made in reducing the reflection of polished surfaces by coating with thin films suggested an investigation of the theoretical foundation of the observed facts by a rigorous solution of Maxwell's equations as applied to such films. The problem is to develop a theory of integration of these equations for the case in which the dielectric constant, the electrical conductivity and the magnetic permeability are not constants but are functions of one of the space coordinates x,y,z, for example of z. These three functions can be continuous or discontinuous corresponding to a continuous or discontinuous arrangement of plane layers perpendicular to the z axis. It is found that under these assumptions the electromagnetic equations can be integrated. The most interesting application of this integration theory is to the propagation of plane waves in metallic or dielectric layers. The result can be described as follows. A periodic oscillator placed at a great distance from the layers produces with increasing time an electromagnetic field

oscillating periodically. This field consists of two plane waves; the reflected wave traveling backward, and the transmitted wave traveling forward. The simpler case of normal incidence is first treated. It is found that the amplitude $a(z)$ of the reflected wave and the amplitude $b(z)$ of the transmitted wave satisfy a system of ordinary differential equations of first order. If the layer system consists of several homogeneous layers separated by parallel planes, the differential equations are replaced by linear recursion formulae of first order. The integration of both types of equation can be reduced to the problem to determine the ratio $R(z)=a(z)/b(z)$. A quadratic differential equation of Riccati's type is found for $R(z)$; in case of the discontinuous multilayer a simple collinear recursion formula replaces this equation. Conditions for zero reflection from multilayer films have been derived from these equations. The case of oblique incidence is treated analogously. Two different sets of linear equations are now obtained, corresponding to the normal and parallel components of the electromagnetic vectors.

2. Observations on Low Reflecting Bi-Layer Films of Metals and Dielectrics. H. OSTERBERG, *Spencer Lens Company.*

Surfaces with very low reflecting power were obtained by evaporating first a thin layer of aluminum or rhodium upon glass and next a thicker layer of cryolite, magnesium fluoride or quartz. For monochromatic light and a suitable angle of incidence, the reflecting power appeared to be zero in one sample. Slight increases in the transmission were occasionally observed, but ordinarily slight decreases in transmission resulted with the application of these bi-layers. This method is of practical value in producing surfaces of low reflecting power where gains in transmission are immaterial. It is generally more effective in reducing the reflecting power than single films of magnesium fluoride or cryolite. Unexpected phenomena were observed when uniform layers of dielectric were evaporated upon metal wedges. These wedges were usually controlled to give a metal-glass reflectivity from 4 to 20 percent and were coated with dielectric layers of thickness in the range 0.06 to 0.3 micron. First, the variation in reflecting power along the composite wedge was unexpectedly slow. Thus the 4 to 18 percent range of metal-glass reflectivity was reduced to the narrow range 0 to 3 percent by the addition of, for example, magnesium fluoride layers. Secondly, it was not understandable that metal-glass reflectivity of the magnitude of 18 percent can be reduced to 2 percent by the addition of a thin film of magnesium fluoride. To our knowledge, existing treatments of the Maxwell field equations were not adequate for explaining the above and related phenomena. Solutions which are adequate for explaining the observed facts must be capable of predicting the reflecting power of and the phase changes from metallic films as functions of their thickness. These solutions must also include the more complicated interactions which take place among multilayers of both metal and dielectric films. A rigorous solution was accordingly attempted and found at this laboratory. Experimental results are in excellent qualitative agreement with this theory. A study of bi- and multi-layers of metals and dielectrics promises to be of value both practically and for the purpose of finding the applicability as well as the limitations of the Maxwell field equations.

3. Optical Characteristics of Metallic and Dielectric Bi-Layer Films on the Basis of Maxwell's Equation. M. C. TROUTMAN, *Spencer Lens Company.*

Maxwell's theory has been applied to the special case of a plane wave front incident normally in one or two homogeneous thin layers of metals or dielectrics coated on glass surfaces. The purpose is to determine the reflection, absorption and transmission produced by these films. The main results of a general theory are certain recursion formulae for the ratio of the amplitude of the reflected ray to the transmitted ray. These formulae allow the determination of this ratio from surface to surface. These formulae were adapted for the purpose of convenient numerical investigation as well as for the problem of obtaining the more essential physical interpretations involved. The indices n and nk and the thicknesses are the variable parameters. Graphical representations and numerical methods were developed by the use of simple facts of the theory of functions of complex variables. In two special combinations, namely, magnesium fluoride on aluminum on glass, and sphalerite on aluminum on glass, the reflection, absorption and transmission have been determined numerically for all combinations of the thicknesses of the two layers. The indices n and nk necessary in these computations were obtained from the *International Critical Tables*. The graphs representing the numerical results show that in the case of MgF_2 on Al on glass at least one combination of thicknesses exists for which the reflection is zero with monochromatic light. In the case of sphalerite on aluminum, large variations occur in the reflectivity as the relative and absolute thicknesses of the two layers are changed. Another remarkable variation takes place in the absorption in the metal film as the thickness of the applied film of sphalerite is varied. The behavior of sphalerite on aluminum is markedly different from that of magnesium fluoride on aluminum. The numerical results are in good agreement with observations upon films evaporated at this laboratory.

4. Coherency Relations for the Light Scattered by Colloids. HANS MUELLER AND GEORGE J. YEVICK, *Massachusetts Institute of Technology.*

According to R. S. Krishnan[1] the Tyndall light of colloids can be considered as consisting of four components V_v, V_h, H_v and H_h, where, for example, V_h denotes the scattered light which vibrates vertically and originates from the horizontally vibrating component of the incident light, the directions of incidence and of observations being in a horizontal plane. For vertically vibrating incident light the scattered light, consisting of V_v and H_v, is linearly depolarized. This fact implies that V_v and H_v are incoherent. Analogous results with the incident light vibrating horizontally show that H_h and V_h are incoherent. Our investigation deals with the question whether any other pair of components is coherent. Theoretical considerations[2]

predict that this should be the case for the two pairs V_v, H_h and V_h, H_v.

This prediction has been verified for various colloids and suspensions in two types of experiments. In the first type the incident light is plane polarized at an angle α to the vertical. Observation of the Tyndall light through split Polaroids shows that the orientation β of the axis of depolarization depends on α. In the second experiment the incident light is elliptically polarized and compensator measurements of the scattered light show it to be partially elliptically polarized. The $\alpha(\beta)$ relation of the first experiment and the relation between the ellipticities of the incident and scattered light in the second experiment are found to be in quantitative agreement with the prediction of the theory.

[1] R. S. Krishnan, Numerous papers in Proc. Indian Acad. Sci. Vols. I–VII (1934–1938).
[2] Hans Mueller, Proc. Roy. Soc. London **A166**, 425 (1938).

5. Calculation of the Color of Pigmented Plastics. J. L. SAUNDERSON, *The Dow Chemical Company.*

For routine application in the plastics field, the six-constant theory of Duntley[1] dealing with the color of pigmented materials is inconvenient both in application of the theory and in the experimental procedure described. In this paper the usefulness of the two-constant theory for the calculation of the color of opaque pigmented materials is demonstrated. Convenient methods suitable for routine use for determining the optical constants of dyes and pigments and for making the surface corrections necessary for use with a General Electric recording spectrophotometer are described. The calculations of the colors of mixtures of pigments and dyes are illustrated by means of spectrophotometric curves. The method has been used with considerable success by the author for making calculations on the color of pigmented plastics. After a catalogue of dyes and pigments has been built up, it is possible to calculate the mixture required to achieve a desired color. The method is therefore useful in color matching, and for general trouble-shooting in color work.

[1] S. Q. Duntley, J. Opt. Soc. Am. **32**, 61 (1942).

6. Adaptation in Colorspace. DOMINA EBERLE SPENCER, *Massachusetts Institute of Technology.*

The trichromatic system specifies any colored light (with respect to its color matching properties) by three numbers, and the color can be represented by a point x^k in affine 3-space. The data on which the C.I.E. system is based were obtained with colored lights and a dark surround. But the colors of ordinary experience may be seen under other conditions. The trichromatic system is quite incapable of showing, for instance, that a bright orange light with dark surround becomes a brown light when a white surround of sufficient brightness is used. The purpose of this paper is to inquire into the possibilities of introducing the *adaptation of the eye* into the color specification system. The results can be represented by points in a 5-space, but a more convenient method is to introduce a new tensor p^{kl} into the 3-space. This new tensor, a form of *rhabdel*,[1] has been studied by mathematicians but has had no previous applications. Rules for addition and for multiplication by a scalar are stated. The false nature of the Ostwald gray scale[2] is pointed out and possibilities of the new system in the study of color harmony are mentioned.

[1] D. E. Spencer, "A tensor interpretation of Study's *Geometrie der Dynamen*," M.I.T., PhD thesis, 1942.
[2] W. Ostwald, *Farbkunde* (S. Hirzel, Leipzig, 1923).

7. A Grating Spectrograph of Fabricated Steel. J. W. FORREST AND H. W. STRAAT, *Bausch & Lomb Optical Company.*

The authors will describe a grating spectrograph of the classical Wadsworth type for use with a grating of 4-meter radius and having 25,000 lines to the inch. The spectrograph is a complete unit in the same sense that the ordinary Littrow spectrograph is complete. All parts are assembled permanently on a single chassis. The mechanical structure departs widely from current practice in that the entire chassis is of welded sheet steel. The assembled unit has shown marked resistance to vibration troubles arising from adjacent heavy machine installation. The shutter, traveling beam, etc., are operated electrically from the plate position. The instrument accepts all standard accessories. The instrument is equipped with a magazine film holder designed to accept standard rolls of 35-mm motion picture film. This holder is arranged so that the receiving chamber may be detached and taken to the dark room without disturbing the holder. The process of removal of the chamber automatically cuts the film and makes the closure of the holder on the instrument.

8. An Improved Electrode Holder for Spectrographic Analysis. BOURDON F. SCRIBNER AND CHARLES H. CORLISS, *National Bureau of Standards.*

An electrode holder has been constructed at the National Bureau of Standards to meet the need for higher speed in miscellaneous spectrographic testing involving the use of a variety of excitation conditions and electrode sizes and shapes. The holder consists of water-cooled copper clamps, insulated for high voltage, and mounted rigidly on heavy yokes which move vertically on two supporting rods. One jaw of a clamp moves on rigidly aligned ways and the jaws are designed to hold, in close contact, electrode rods of various diameters up to $\frac{1}{2}$ inch. An accessory which may be quickly mounted provides for clamping sheet or disk samples. The assembly is mounted on a heavy base which locks in place on an optical bench and is inclosed in a grounded sheet metal housing equipped with a safety switch. Controls for vertical displacement of the electrodes and for lateral motion of the assembly extend outside of the housing. Provision is made for setting electrode gap distances to 0.1 mm by a graduated drum. All controls are designed for rapid interchange and adjustment of electrodes for the three modes of excitation, the d.c. arc, the a.c. arc and the high voltage spark. Details of the construction and application of the holder will be given.

9. Spectrographic Analysis of Nickel Alloys Using Pressed Pellet Electrodes. C. J. NEUHAUS, *The International Nickel Company, Inc.*

The procedure described in this paper deals with the determination of iron, magnesium, and manganese in

nickel using spark excitation, a pressed pellet as sample electrode, and a pointed graphite rod of $\frac{1}{4}''$ diameter as auxiliary electrode. The pellet electrode has been pressed from millings of such size as to pass through No. 20 mesh. The use of only one pellet electrode in contradistinction to methods developed by other workers using two pellets permits an analysis of a sample of 1 gram or less which may be slected by proper sampling. Pellets may also be prepared from thin sheets or fine tubing by cutting the material in small particles and subsequent compressing in a die under 340,000 psi. The preparation of millings and a tentative method for the pressing of pellets are described. Experiments relative to the determination of optimum conditions are discussed and graphs pertaining to this are shown. The spectrographic set-up, the photographic and densitometric procedures as well as the evaluation of transmission data are discussed. Reproductions of the analytical curves prepared for the following ranges are given:

Iron	from 0.020 percent to 0.5 percent
Magnesium	from 0.040 percent to 0.3 percent
Manganese	from 0.050 percent to 1.0 percent.

The standard deviation determined from the manganese data for repeated determinations of the same standard is approximately 3 percent. With a single routine determination of the same element a standard deviation of 5 percent may be expected. With twenty-four samples and a calibration pattern placed on a 4×10 plate the working time per element determination amounts to approximately 4.5 minutes.

10. Quantitative Spectroscopy Applied to Some Impurities in 70-30 Cupro-Nickel. WALTER D. FRANCE, *Scovill Manufacturing Company.*

Because of the present emergency, the increased production of ships had made it necessary to speed up, in every way possible, the manufacture of seamless condenser tubes. A quantitative spectrographic method for the analysis of zinc, lead and iron in 70–30 cupro-nickel, a condenser tube alloy is described. The method is based on the use of a 10-ampere, 220-volt d.c. current through carbon electrodes. The advantages of weighted and pilled samples are described. The method having been designed to handle as many as one hundred samples a day incorporates only the necessary steps. Exposure time is set at a minimum by focusing on the slit. Emphasis is put on photographic technique. The use of a calculating board is described in the application to the determination of iron.

11. A Stigmatic Grating Spectrograph for Industrial Laboratories. RICHARD F. JARRELL, *Jarrell-Ash Company.*

A self-contained grating spectrograph is described which employs a 6-inch diameter, 15,000 line per inch aluminum on Pyrex concave grating in the stigmatic mounting originally suggested by Wadsworth and first applied in a practical way by Meggers. In this mount the light is collimated by a concave mirror before reflection from the grating, whose face is mounted directly above the pivot of, and perpendicular to, a sliding steel beam at the other end of which the plateholder is mounted, at approximately half the radius of curvature. Under these conditions the calculated image at the center of the plate is strictly stigmatic, while the horizontal and vertical foci depart from strict coincidence away from the center by a factor of the $\cos^2$ of the angle to the perpendicular. For a 21-foot radius grating at 10 inches from the center of the plate the difference is calculated at 18 mm, which at the focal length used, is a permissible tolerance for the use of sectors and diaphragms directly before the slit. Use of the mirror about 2.5° off axis introduces a very slight additional astigmatism. The plateholder takes two $4''\times10''$ plates, so that an unusually wide range of spectrum can be covered at one setting. A single cam keeps the plate automatically in focus as the beam is moved to bring additional wave-length regions onto the plate. The pointer and scale which indicate the wavelength and the switch for the gear motor which moves the bar are located at the front of the instrument. Also on the front operating panel are the switches which control the racking of the plate, the scale for the plateholder, and timers for the electrically-operated slit shutter and for timing the pre-sparking period and exposure. A gear shift at the front base provides for two slow motion drives for use in continuously moving plate exposures.

12. A New Spectroscopic Source Unit. M. F. HASLER (*with H. W. Dietert of H. W. Dietert Co.*), *Applied Research Laboratories.*

A new type of spectroscopic source unit has been developed that allows a wide variety of discharge conditions to be achieved. These include the oscillating spark with variable current, frequency, and damping; the critically damped spark of variable time; the overdamped d.c. spark of variable current and damping; the d.c. spark-arc; and the pulsating d.c. arc of variable time and current. The wide variety of discharge conditions are achieved by a high voltage synchronous ignitor, 12,000 v; a medium voltage rectifier, 850 v, for charging a bank of condensors; a variable resistance; and a variable inductance. Exact reproducibility of the discharge is achieved by charging condensers on one-half of the sixty-cycle current, and discharging on the other half-cycle. Studies made with this source unit include current *vs.* time of discharges as obtained on an oscillograph; concentrational sensitivities of various elements in various matrices; reproducibility of the spectral characteristics of the discharge; changes of line intensity in the discharge with changes of concentration in the electrode material. The results of these studies indicate that this source unit should find many applications in industrial spectro-chemical testing where special discharge conditions are required that are not obtainable from present source units.

13. Electronic Voltage Regulator for Precise Densitometric Measurements. HARRY W. DIETERT, *Harry W. Dietert Company* AND M. F. HASLER, *Applied Research Laboratories.*

The electric power input into a projection lamp of a densitometer used to measure the intensity of spectral lines

should be controlled so that light output of the projection lamp is held constant. An electronic voltage regulator has been developed where the power output regulating medium is obtained by having the light of two lamps beam on a photo tube. The unit is a high powered electronic tube amplifier, controlled by a photo-tube bridge which in turn is illuminated by two lamps, one operated from the output voltage and the other from the input. Compensation is not instantaneous but sufficiently fast so that line transients do not appear on the densitometer meter or galvanometer. Frequency fluctuations do not affect the output voltage. The correction factor for the new regulator is thirty. Thus, a 1 percent change in input voltage gives 0.03 percent change in output voltage which may result in an 0.08 percent change in the densitometer reading. A 5 percent change in input voltage gives a 0.4 percent change in densitometer reading. A good service line should not vary by more than plus or minus 3 volts over half-hour periods. Variations in densitometer readings under these conditions would be less than plus or minus 0.24 percent while reading a single plate or film.

14. Photodissociation of Organic Molecules, One or More Bonds at a Time. GLADYS A. ANSLOW AND EVANS VAUGHAN, *Smith College.*

Correlating the results of experiments in photolysis and in electronic ionization with the absorption spectra of organic molecules, we conclude that absorption of photon energy results in vibration excitation of a double bond and the simultaneous rupture of one or more neighboring bonds. By utilizing published spectroscopic studies of the simpler organic molecules, spectral regions may be identified with the dissociation of one C−C, one C−H, or with various combinations of two or more of these bonds, the characteristic vibration structure of C=C, C≡C, and C=O being superposed thereon. The C−C bands appear in the visible, C−H in the near ultraviolet, and the others in the ultraviolet and the Schumann regions. In the latter regions absorption bands occur which may be identified with the rupture of C=C and C≡C bonds. Dissociation energies are calculated from the vibration centers near the long wave-length edges of the absorption bands and agree both with thermochemical and electron collision values. When two or more single bonds are simultaneously broken the absorbed energy is approximately equivalent to the sum of the energies which break the bonds separately.

15. Determination of the Concentration of Benzene and Toluene in Air by a Spectroscopic Method. PETER A. COLE, *National Institute of Health.*

A convenient spectroscopic method of qualitative and quantitative analysis of air samples for benzene and toluene is described. The apparatus consisted of a hydrogen discharge tube which served as a source of ultraviolet radiation, a fused quartz absorption cell of 120-cm length, a rotating step sector disk for plate calibration, and a medium sized quartz spectrograph. This method is sufficiently precise for application in the range of toxicological importance when only a 500-cc sample of air is used. The method is limited to those aromatic vapors which have discrete band spectra in the near ultraviolet region of the spectrum. A convenient sampling bulb is described which is useful for air samples containing inflammable solvents. Working curves relating intensity of absorption to concentration are shown for two important solvents, benzene and toluene.

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